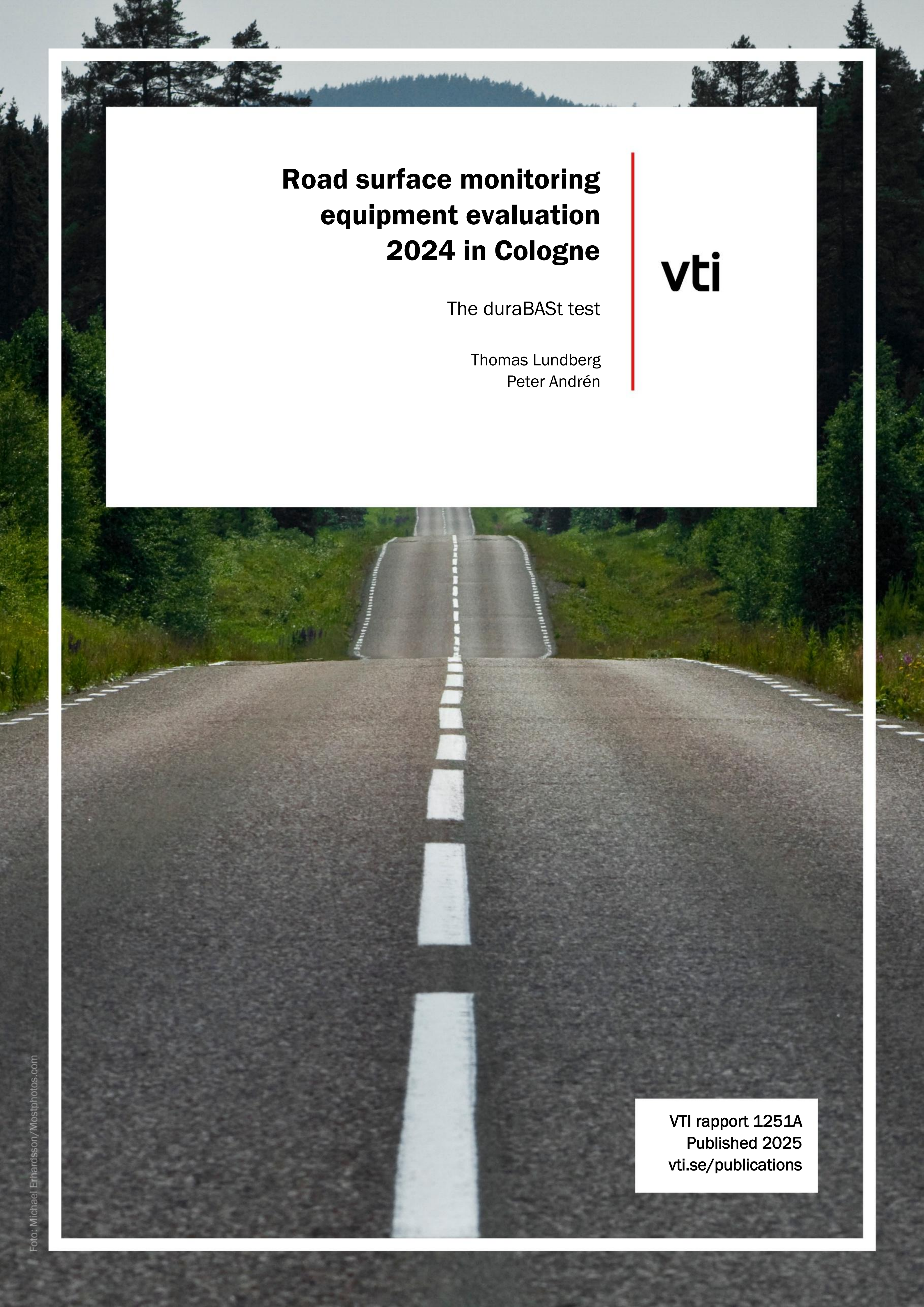

Road surface monitoring equipment evaluation 2024 in Cologne

The duraBASt test

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Kort sammanfattning

Denna studie utvärderar den tekniska prestandan hos olika system för vägytemätning, med särskilt fokus på deras validitet och repeterbarhet. Vägytemätning är avgörande för effektiv underhållsplanering och kräver tillförlitliga samt heltäckande data om vägarnas skick. Moderna trender betonar insamling av flera typer av data vid ett och samma tillfälle, vilket ökar effektiviteten, minskar miljöpåverkan och sänker kostnaderna.

De testade systemen delas in i tre kategorier:

- Profilometrar – Använder vanligtvis linjelaserteknik för profilering och sprickdetektering.
- Mobile mapping (områdesmätning) – Använder ofta Lidar-skannrar och kan använda antingen terrängmodeller eller kombination av punktlaser och accelerometrar för profilmätning.
- Uppkopplade fordonssystem – Baserar sig på fordonens sensorer, monterade extra accelerometrar eller datainsamling via smartphone.

Utvärderingen genomfördes vid testanläggningen duraBASt, enligt metoder etablerade av svenska och finska väghållningsmyndigheter. Validiteten bedömdes genom att jämföra deltagarnas resultat med två referenser: mätningar med dedikerade referenssystem samt ett genomsnitt av deltagarnas resultat (med undantag för uteliggare). Repeterbarheten utvärderades genom att beräkna standardavvikelsen mellan upprepade testkörningar.

Viktiga tekniska resultat:

- Mobile mapping-system uppvisade bäst validitet och repeterbarhet för huvuddelen av variablerna, med vissa av profilometrarna som nådde liknande resultat.
- Uppkopplade fordons har generellt sämre överensstämmelse med referens i jämförelse med de andra kategorierna och också sämre repeterbarhet (indikerat av högre standardavvikelse).
- För International Roughness Index (IRI) nådde mobile mapping-systemen 81 % validitet och 0,13 mm/m i repeterbarhet, vilket totalt sett var bättre än de andra kategorierna.
- Vad gäller längsprofilen visade alla system god överensstämmelse med referensdata för våglängdsbandet 4 till 10 meter; prestandan försämrades utanför detta intervall.
- De flesta system uppfyllde repeterbarhetskraven enligt svenska krav för mätning av längsprofil.
- De flesta system uppnådde noggrann positionering (latitud, longitud, höjd), med avvikelser på endast några centimeter.
- Körfältsbreddsmätningarna var mycket precisa, med de flesta system presenterade ett resultat inom en centimeters avvikelse från referensmätningen.

Sammanfattningsvis presterade samtliga testade system relativt väl, men mobile mapping-system gav de mest robusta tekniska resultaten både vad gäller validitet och repeterbarhet. Profilometrarna presterade också bra. Uppkopplade fordonssystem, även om de var mindre precisa, erbjuder praktiska fördelar för god täckning och en frekvent datainsamling.

Nyckelord

Systemjämförelse av vägytemätare, Test av vägytemätning, Mobile mapping test, Test av uppkopplade fordon för vägytans egenskaper, Vägyteegenskaper

Abstract

This study evaluates the technical performance of various road monitoring systems, focusing on their validity and repeatability. Road monitoring is crucial for effective maintenance planning, requiring reliable and comprehensive data on road conditions. Modern trends emphasize collecting multiple types of data in a single pass, which increases efficiency, reduces environmental impact, and lowers costs.

The systems tested are divided into three categories:

- Profilometers – Typically use line laser technology for profiling and crack detection.
- Mobile Mapping Systems – Often employ Lidar scanners and can use either terrain models or point laser/accelerometer combinations for profile measurement.
- Connected Vehicle Systems – Rely on vehicle sensors, additional accelerometers, or smartphone-based data collection.

The assessment was conducted at the duraBASt test facility, following methods established by Swedish and Finnish road authorities. Validity was measured by comparing participant results with two references: dedicated reference system measurements and the average of all participants (excluding outliers). Repeatability was evaluated by the standard deviation across repeated test runs.

Key technical results:

- Mobile mapping systems demonstrated the highest validity and repeatability across most parameters, with some profilometers achieving similar results.
- Connected vehicle systems did not agree with reference as good as the other categories and poorer repeatability (indicated by higher standard deviation).
- For International Roughness Index (IRI), the mobile mapping category achieved 81% validity and 0.13 mm/m repeatability, in total a better result than the other categories.
- In terms of longitudinal profile, all systems showed good agreement with reference data for the wavelength band 4 to 10 meters; performance declined outside this range.
- Most systems met the repeatability requirements set by Swedish standards for longitudinal profile measurement.
- Accurate positioning (latitude, longitude, height) was achieved by most systems, with deviations of only a few centimeters.
- Lane width measurements were highly precise, with most systems accurate to within one centimeter of the reference measurement.

In summary, while all tested systems performed reasonably well, mobile mapping systems provided the most robust technical results for both validity and repeatability. Profilometers also performed well. Connected vehicle systems, although less precise, offer practical advantages for widespread, frequent data collection.

Keywords

System comparison of road monitoring equipment, Road surface monitoring test, Mobile mapping test, Test of connected vehicle for road monitoring, Road surface characteristics

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Summary

Road monitoring is the major source of information for maintenance planning in many countries. Road monitoring includes a lot of disciplines and techniques. The key issue for a road administration is to have an accurate picture of the standard of the road network today, and the coming three to five years. In addition to accuracy, the information should provide a sufficiently comprehensive picture of the road's condition to determine where, when, and how the road should be maintained.

A test like the duraBASt test requires a lot of planning. This study can be divided into nine phases.

1. Idea phase – considering the feasibility and practicality of conducting a test.
2. Budgeting and financing phase – estimating the costs of carrying out the trial and securing commitment from clients and participants to support the project.
3. Detailed planning phase – thoroughly planning all activities, including logistics, equipment, consultants, in-house staff, as well as liaising with duraBASt and participants. This stage also involves a site visit to duraBASt prior to the test.
4. Reference measurement – the reference measurement should ideally be conducted as close as possible to the participants' arrival.
5. Test execution – managing logistics regarding when participants should measure, adapting to weather conditions, maintaining contact with participants, and ensuring contingency days are included in the plan are all extremely important.
6. Data delivery – a set date for data delivery, providing feedback on the delivered data, and allowing participants to correct obvious errors in their submission.
7. Analysis and troubleshooting – errors in the submitted data are often identified during the analysis phase; some can be easily corrected, while others cannot be adjusted.
8. Reporting – the project as a whole must be described and summarized in this phase, which is often underestimated in terms of the time required.
9. Presentation – the results are presented; from the outset, this project was presented at the Erpug conference in Lisbon Portugal 2025 (www.erpug.org).

Undoubtedly, phases 3, 5, and 8 are the most demanding. Convincing the client of the project's importance, both for the organization and the industry as a whole, is always a time-consuming process. Adverse weather conditions affected the execution of the test, necessitating a revision of the program schedule and utilization of contingency days. The reporting process has proceeded satisfactorily, despite numerous revisions and reviews of the results (the current result version is 33).

There are many more parameters to consider for a client commissioning a measurement (e.g. a road authority):

- Safety – can the measurement be carried out safely, without disturbing other road users?
- Environmental aspects - can the measurement be carried out with a minimum of environmental impact?
- Production speed – are the measuring system or systems able to carry out the measurement assignment in the specified time?
- Processing speed – how quickly can data be transformed into information about the road's condition and be utilized in daily operations (maintenance planning)?
- Cost – is the result from the measurement cost-effective and competitive compared to other alternatives?
- Accuracy – does the measurement meet the quality required by the client?

This study considers only the technical quality of the participating systems, without revealing who produced which result. Only the participants know the code for their own systems. To compare the performance of various techniques, the systems are organized into three categories: profilometers, mobile mapping systems (based on the method used to assess the transverse profile), and connected vehicle systems. The profilometer category is relatively uniform, with most participating systems employing line laser technology for transverse profiling and crack detection. In the mobile mapping category, Lidar scanners are commonly used to measure the transverse profile, while the longitudinal profile can be derived either from the terrain model generated by Lidar data or via a "profilometer technique" using a point laser combined with an accelerometer. The connected vehicle category encompasses a wide range of techniques, which may involve utilizing a vehicle's own sensors for data collection, mounting additional accelerometer sensors on the vehicle, or incorporating sensors and cameras from smartphones.

The test was conducted following procedures established by the Swedish Road Administration and the Finnish Transport Infrastructure Agency. The primary goal was to determine system accuracy (validity) and assess repeatability. Participant results related to validity were compared against two references: one from dedicated reference measurements using the Swedish National Road and Transport Research Institute's (VTI) systems, and another based on the average results of participating companies. To eliminate outliers, only data falling within the central portion of a particular variable were considered. Specifically, the average was calculated using the middle 50% of the data, excluding the lowest and highest 25% of values. In this assessment, both references were found suitable for use. However, the method using the participating systems as reference is not recommended when there are fewer than eight to ten participants, due to the increased risk of bias in reference. The tests conducted in this study utilized the 20-meter average values for each variable as input data. Repeatability is tested from the standard deviation of the repeated runs at 20-meter section size. The goal was to do ten rounds of the test track, but because of the weather and tight time schedule some participants only managed to do eight repetitions. This does only affect the test marginally. This test was carried out at duraBASt, a test facility administered by the Bundeanstalt für Straßen und Verkehrsvesen (BASt). Four sections were used in the tests, which made it possible for the measurement of all sections to be carried out in one round around the test facility.

The result is predominantly good, when compared to the requirement limits used in Sweden and Finland. Many of the tested systems meet these limits. In Sweden and Finland, these tests are carried out on public roads, on selected sections that cover the normal measurement ranges for the variables being tested. The conditions at the test facility duraBASt were more challenging than the equivalent on public roads, mainly due to the severe unevenness in one section. The validity and repeatability results of the three system categories are compiled in Table 1.

Table 1. Validity and repeatability: overall average results per category (P – profilometers, MM – mobile mapping, CV – connected vehicle).

	Validity			Repeatability		
	P	MM	CV	P	MM	CV
IRI	73%	81%	50%	0.18	0.13	0.60
Rut depth 3.2m	79%	75%		0.15	0.12	
Sliding Wire Rut Depth 2.0m	74%	90%		0.15	0.09	
Crossfall Regression	96%	99%		0.07	0.02	
Hilliness	100%	100%		0.05	0.02	
MPD	70%	43%		0.03	0.04	
Latitude[1]	39%	87%		0.39	0.07	0.32
Longitude				0.21	0.09	0.61
Height	88%	100%		0.24	0.03	

Overall, the mobile mapping systems perform best in this test, this applies to both validity and repeatability. The systems with best performance in the profilometer category have results close to the results from the mobile mapping systems. The connected vehicle category shows the poorest agreement with reference measurements and poorer repeatability. This was expected; the systems are not as complex but on the other hand easy to use and data is often collected frequently. Connected vehicle (CV) systems often have different objectives than traditional road monitoring. CV measurements are primarily aimed for previously unmeasured roads at network level in developing countries, on gravel roads or in cities or at wintertime when normal road monitoring is not suitable to do. To increase quality, crowd sourcing is used to collect multiple measurements at the same place.

The ability to give a correct IRI-value (International Roughness Index) while breaking-stopping-accelerating (stop-and-go) was tested at one of the sections. The stop-and-go test shows good results for the mobile mapping participants whereas profilometers, connected vehicles and smartphones systems are clearly negatively affected in such situations.

The Power Spectrum Density of the Longitudinal Profiles shows each system's ability to get information about the road surface in the wavelength band between 0.2 up to 100 meters. All systems have good agreement with the reference in the wavelength band 4 to 10 meters. Above and below these boundaries the agreement is poorer. Several systems have, however, good agreement through the whole spectrum. An additional test of the longitudinal profile has been done, using the Swedish control method for repeatability. The same method is also used for validity in this test. The repeatability results are generally good; most systems meet the requirements used in Sweden. The participants' longitudinal profiles are also in good agreement with the reference data.

Cracks have been difficult to analyze in detail. Each participating measurement system's results were compared to the reference across the entire measurement width of 3.8 meters, rather than at the five predetermined zones. The agreement between the participating systems' measurements and the reference measurement is, however, good.

The task of determining the position of five objects in latitude, longitude and height shows very good results. Most systems could position the top of a cone within a few centimeters.

[1] The longitude validity is not only done from the longitude, but as the difference between the reference and participants longitude and latitude.

Finally, the participants' ability to measure a correct lane width were tested. Four temporary pairs of road markings were placed at one of the sections. The average distance between the road markings (18.75 meters long) was compared with reference measurement. Most systems managed to measure a "lane width" within 1 centimeter from the reference measurement. This is very good and useful data.

Preface

This study has been possible thanks to contributions from eight road authorities in Europe who generously contributed to the funding. The eight road authorities are:

- The Norwegian Public Road Administration
- Agency for Roads and Traffic (Flemish region, Belgium)
- The Swedish Transport Administration
- ASFINAG (Austrian publicly owned corporation)
- The Finnish Transport Infrastructure Agency
- Rijkswaterstaat (the Netherlands)
- The Danish Road Directorate
- Road and Motorway Directorate of the Czech Republic.

In addition to these grants, the Federal Highway and Transport Research Institute (BASt) has both provided its duraBASt test facility for the tests and has been responsible for the safety of the tests, which was a prerequisite for being able to carry out the tests.

The conference organization ERPUG has also contributed funds from previous conferences. Finally, the participants in the test contributed with the start-up fee for the tests.

As the project manager for the tests, it has been a pleasure to work with the professional team from VTI who made the reference measurements and the extremely helpful colleagues from BASt. The participating companies were very patient and understanding of the weather concerns we had and carried out all measurements professionally and smoothly within the set time.

My colleague at VTI, Peter Andrén, has taken primary responsibility for analyzing the submitted data, and his work has been executed with thoroughness and professionalism.

Given another opportunity, I'd do this again, only better.

Linköping, Sweden, October 2025

Thomas Lundberg
Project manager

Granskare/Examiner

Johan Egeskog, VTI.

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Abbreviations

MPD	Mean Profile Depth
IRI	International Roughness Index
PSD	Power Spectrum Density
Ref	Reference established by dedicated reference measurement
Sys_ref	Reference established by averaging the results from the participants
TermID	Numerical code for identification of variables. Ex. 1287 for IRI in right wheel track
WLP	Weighted Longitudinal Profile
P	Profilometer system category
MM	Mobile mapping system category
CV	Connected vehicle, smartphone and response system category

1. Introduction

Roads play an important role in the means of transportation for our society. Regardless of the vehicle type, truck, car, electric or powered by fossil fuel, well-functioning roads is a must. The annual budget for construction and maintenance is very large, but this is necessary to maintain and improve the standard of the infrastructure. In Sweden alone, about €300 million is spent every year on maintaining the state-owned paved roads (The Swedish Transport Administration, 2024). Considering this, it is of great importance that decisions and prioritization of road management are based on objective, relevant and correct data with known accuracy. Information regarding the road surface condition and deterioration over time is the most important information to strategically and successfully manage the available resources. Therefore, it is vital to assess the condition of the roads – that's why accurate and reliable data is needed. The data should have the accuracy to serve the necessary purpose. Road condition monitoring with profilometers has been the primary way for the road operator to assess the condition, simply because it's accurate, cost effective and available. The data are used in pavement management systems (PMS) to plan and prioritize the maintenance in maintenance plans for the coming years. The overall objective for the road operator is to have roads that are safe, comfortable, and designed and built to last for a long time.

A trend in road monitoring is to collect as much useful data as possible in one measurement. Take Sweden as an example, the Swedish Transport Administration requires, beside the traditional road surface monitoring, also monitoring of the road surroundings with Lidars and 360-cameras. As systems continue to expand, the volume of data is rising exponentially. This process requires sophisticated measurement systems and extensive data management. The data volume has become so large that it can no longer be uploaded via FTP; therefore, the current alternative is to transfer the data using hard drives. The advantage of combining measurements, by doing multiple measurements at the same time, is that it decreases the amount of driving required, thereby enhancing safety and reducing environmental impact. Additionally, the cost of a combined measurement is lower than if two separate contracts were established.

In recent years, alternatives to profilometers have emerged, and LiDAR-based mobile mapping systems are becoming increasingly accurate and more capable. From only being used to describe the surroundings where the measurements are made, also the road surface has been a subject for the high quality measurements. Today several mobile mapping systems can scan the road surface with an accuracy that no one believed possible 10 to 15 years ago. Another important complement to traditional road monitoring is data from connected vehicles and smartphone-based systems. These are often systems with less accuracy, but the frequency of the measurements makes it interesting for the road operators to fill the gaps between the profilometer or mobile mapping measurements, that are normally done once a year or even more seldom. Wintertime in the Nordic countries is of special interest to monitor because of what happens when the ground frost is deep during the cold months, when profilometers normally cannot be used.

2. Purpose

This project has the purpose of gathering different types of road monitoring equipment, especially European systems, to establish the accuracy of different measurement techniques. The test will not reveal the company names, only what type of system is connected to the presented results. The systems are divided into three categories,

1. Profilometers (P) – traditional profilometers normally with a combination of line lasers and point lasers, but also systems with solely point lasers.
2. Mobile mapping systems (MM) – systems based on Lidar (Light Detection and Ranging) which is a rotating laser-based measurement system used to scan the surrounding of the road and the road surface. Since some systems have a combination of Lidar and point lasers, the decisive argument for selecting system category has been the type of equipment used for transversal evenness. If Lidar is used for assessing transversal evenness the system will be placed into this category.
3. Connected vehicles and smartphone systems (CV) – Connected vehicles uses the standard sensors/data in the vehicle to calculate and describe the condition of the road. Smartphone systems have the same principles – to use the sensors in the phone to assess the road condition. This category also includes response evenness measurement where external equipment is mounted and used to assess the variables.

The purpose is to describe the overall performance of all systems but also individual performance for the categories described above. The analysis of the performance will be divided into three tests, validity, repeatability and speed dependency, which will decide the essential components for a reliable measurement.

The benefits of this test for the road operator are to get objective and reliable information on the performance of different types of road monitoring equipment. The information could be used in the procurement process to set requirements for the services and to get inspiration and knowledge about the available systems on the market. Furthermore, new variables, not earlier used, could be detected.

For the equipment and measurement providers the test serves as a benchmark to see how one system performs compared to other systems of same kind but also compared with other system categories.

The test also provides information about requirements in the procuring process used by the Swedish National Road Administration when selecting supplier for the road monitoring service at network level. This gives information and inspiration when setting up or participating in similar arrangements.

The test will also give an indication of what to expect when buying equipment or a service to assess the road surface condition, either using a well-established technique or new techniques like mobile mapping and connected vehicle and smartphone systems.

Finally, the progress of the European standardization (CEN) will benefit from the results of this test. The data, conclusion and reports provided by the duraBASt testing will be an important input to European standardization and the testing can be seen as pre-normative work for this. The purpose of the CEN standardization is to open the European market and prevent trade barriers. The outcome of the duraBASt test is an important source of information for standardization development in Europe and other parts of the world.

3. Method

There are fundamental properties that must be met for a measurement to be usable. The data measured must yield a result that describes the function or characteristic the user expects it to describe, with sufficient accuracy for its intended purpose – adequate validity. Furthermore, the equipment and operators must be able to reproduce the results from repeated measurements under the same conditions with satisfactorily consistent outcomes – adequate repeatability. If the circumstances of the measurement mean that data is collected under varying conditions, such as speed, pavement type, moisture, etc., it is necessary to define the conditions under which measurements must be conducted – speed dependency. Another aspect, which we have not been able to test at duraBASt, is reproducibility; that is, a supplier's ability to repeat a result with sufficient accuracy when using more than one measurement system.

Three test methods will evaluate the participants.

Initially, validity will be assessed by comparing participant results to two references: specialized reference equipment from VTI (the Swedish National Road and Transport Research Institute) and the average performance of the participating companies. An interval surrounding the reference values is applied to evaluate the participant data. Validity is measured as the percentage of the 20-meter average values that yield results closely aligned with the reference. This is further described in chapter 7.1.

Secondly, repeatability is assessed to determine whether the participant's measurement system and operators are capable of producing consistent results across multiple runs. Repeatability is measured by the 75th percentile of standard deviations for repeated 20-meter average values. This is further described in chapter 7.2.

Finally, speed dependency is evaluated by calculating the percentage difference between the average values of all measurements taken at 30 and 40 km/h. Variables with both negative and positive values are evaluated with the absolute difference between the results in the different speeds. This is further described in chapter 7.3.

The requirements used in technical tests during procurement procedures by the Transport Administrations in Sweden and Finland will serve as a benchmark for the participating companies. The requirements can be found in Annex 1.

4. Sources of error

Every measurement is made under a specific condition which leads to errors. Even the best system and operator produce small errors. The systems are also more or less sensitive to how the measurements are made. The test section itself can also be more or less prone to measurement errors depending on how the vehicle has been driven. Especially the lateral position has an impact on the results. This shows even though the test track at duraBASt is homogenous built with very small variations in the transverse direction. The reference measurements are done static or at very low speeds, from walking speed to 15 km/h. This gives a solid reference measured at the correct lateral position and data with small errors.

In the original description of the test the coordinate system was specified as DE_DHDN / GK_3 (EPSG:31467). The correct coordinate system for the location of duraBASt should have been DE_DHDN / GK_2 (EPSG:31466). All coordinates delivered in DE_DHDN / GK_3 and WGS84 have been transformed to DE_DHDN / GK_2 with the software "gdaltransform" from the GDAL project (see gdal.org). The heights from satellite positioning have been delivered in two formats, the orthometric/geoid height according to DE_AMST_2016 / NH and the ellipsoidal height, as given by GNSS receivers. The GNSS heights have been transformed to orthometric height by subtracting 46.624 meters (the difference between geoid and ellipsoid heights at the test site). Some variables was delivered with the wrong starting point by the participants, meaning the longitudinal matching with reference is poor. The data has been adjusted when there are obvious errors made. All adjustments have been checked with the following criteria: does the adjusted data give a better agreement with reference (better validity result)? – if "yes" – the adjustment is approved and done.

Below are the major sources of error presented.

- Lateral position introduced by the driver.
- Some of the participants in the connected vehicle category assesses evenness as an average of left and right wheel track. The reference is always measured in the right wheel track.
- Incorrect longitudinal start position.
- Measurement sensors out of range because of the bumps at section A.
- Short acceleration phases before start of measurement, sections B and D.
- Less than ideal measurement conditions, because of moisture and rain. (The participants did decide when the condition was ok for their system.)
- Different satellite conditions during the test period.
- Coordinate translation from one system to another.

5. Measurement arrangements

5.1. Test track - duraBASt

DuraBASt (www.durabast.de) provides the possibilities to test road monitoring equipment. The facility has several sections with different features to test the most common variables used for assessing the road surface condition. The complex is operated by Bundeanstalt für Straßen und Verkehrsvesen (BASt). Operating at duraBASt requires you to follow the security instructions stipulated by BASt. All operators and visitors had to carry out a safety briefing before entering the site. Each participant had to wear a safety vest and safety shoes (with steel cap), and the test was supervised by BASt personnel. The maximum allowed speed at the test track is 60 km/h. However, some of the sections are only suitable for a maximum speed of 30 to 40 km/h, depending on the vehicle used. Finally, the vehicle should have reflective signs on all sides of the vehicle.

The test facility enables tests of different variables at different parts or sections, see Figure 1. Every vehicle was planned to do eight to ten repetitions at each section, evenly distributed at two different speeds. The low speed was 30 km/h and the high speed 40 km/h. The maximum speed was set to 40 km/h because of the heavy bumps at one section and short acceleration run-in phase after turning the vehicle at other sections. This was not an ideal speed range to investigate the speed dependency.

Figure 1 Overview of duraBASt. Picture source: www.durabast.de.

The numbers shown in Figure 1 refers to:

1. Longitudinal evenness (not suitable for high speed)
2. Transversal evenness
3. Skid resistance
4. Cracks
5. Texture
6. Road markings

Figure 2 and Figure 3 below show point cloud pictures of the four test sections used in the test.

Figure 2 3D data from sections A (left) and B (right).

Figure 3 3D data from sections C (left) and D (right).

5.2. Participants of the test

At the outset, 28 systems were scheduled to participate in the test. However, due to various circumstances, several participants withdrew, resulting in measurement data from 23 participants being analyzed: ten systems in the profilometer category, eight in mobile mapping, and five in connected vehicles (the category connected vehicle also includes smartphone solutions and response systems).

The participants that delivered data who are included in the analysis are:

- CV Equipment Vectra (NextRoad group), two systems (France) – P
- Norwegian Public Roads Administration (Norway) – MM
- GRID (Czech Republic) – MM
- Roadscanners (Finland) – MM
- Université Gustave Eiffel, three systems (France) – 1 P, 2 CV
- VARS (Czech Republic) – P
- Ramboll (Sweden) – P
- XenomatiX (Belgium) – MM
- Nordic Geo Center (Finland) – MM
- Univrses (Sweden) – CV
- Austrian Institute of Technology (AIT) (Austria) – MM
- Sina ASTM Group (Italy) – P
- NCC Infrastructure (Sweden) – P
- Danish Road Directorate (Denmark) – P

- ARRB Systems AB (Australia) – CV
- Fugro (Netherlands) – P
- Leica Geosystems (Switzerland) – MM
- Geodrom (Czech Republic) – MM
- Mercedes Benz (Germany) – CV
- VTI (Sweden) – P

The systems are described in Annex 3. These descriptions are written by the participants.

5.3. Measurements

Four test sections were used for the test. The validity of the variables, described below (Table 2), was only tested in some of the sections. However, the repeatability was tested using data from sections A, C and D. Section B was short and it was difficult to get up to the right measuring speed at the start of the section.

Table 2 Reference measured variables and sections.

Section	Variables (reference measured)	Figure 1 description	Comments
A	Longitudinal evenness, hilliness, position, texture, transversal evenness and crossfall	1	Used for variables: IRI, Rut Depths, crossfall, MPD, Hilliness, Mega texture, Position, Height, and WLP, and Longitudinal profiles. Length used 240 m. (100 m for Position and Height).
B	Cracks	4	Used for variables: Cracks. Length used 120 m.
C	Transversal evenness, crossfall, hilliness, longitudinal evenness	2	Used for variables: IRI, Rut Depths, crossfall, Hilliness, WLP, and Longitudinal profiles. Length used 180 m.
D	Texture, lane width, objects, wide transverse profile, transversal evenness, crossfall, position, longitudinal evenness	3	Used for variables: IRI, Rut Depths, crossfall, MPD, Mega texture, Position, Height, and WLP, and Longitudinal profiles. Length used 260 m. (100 m for Position and Height).

5.3.1. Reference measurements

Reference measurements were conducted prior to participant measurements. All reference data were collected and analyzed using VTI's in-house software.

Longitudinal evenness

The longitudinal profile is determined through an integrated approach utilizing both a total station (located to the left in *Figure 4*) and the Primal device (located to the right in *Figure 4*). The total station records elevation data at 10-meter intervals along the test section. Between these points, the Primal continuously acquires profile measurements as it moves, capturing data every 4 millimeters. By synthesizing the high-resolution measurements from the Primal with the 10-meter interval data from the total station, a comprehensive "true" reference longitudinal profile of the evenness section is established (see Figure 5). This profile serves as the basis for calculating the reference IRI and WLP in accordance with EN 13036-5:2019 (CEN, 2019). The reference longitudinal profiles are usually high-pass filtered and converted from meters above sea level to millimeters.

Figure 4 To the left, the measurement of 10 m points with total station. To the right, the Primal collects a profile value every 4 mm. Photos: Thomas Lundberg and Linda Corper, VTI

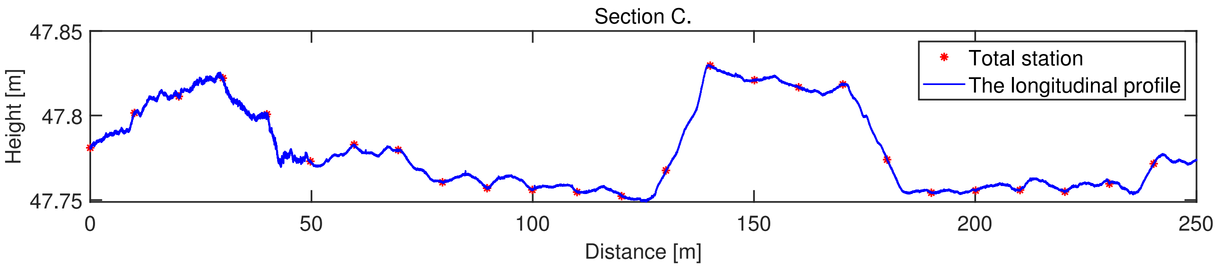


Figure 5 Reference longitudinal profile from test section C.

Transverse evenness and crossfall

The transverse profile is measured using the VTI-XPS method (*Figure 6*) with seven LMI Gocator 2375 sensors across a 3.6 m width. Data is combined with a GPS receiver and inertial measurement unit (OXTS Survey+) to align the profile to the horizon for crossfall calculations.

Figure 6 VTI-XPS, reference for transversal evenness and crossfall. Photo: Thomas Lundberg, VTI.

A transverse profile was obtained every 0.1 m along the longitudinal axis, with a 1 mm sampling interval in the transverse direction. Five measurements using VTI-XPS were conducted within the test section. The centre of each transverse profile was aligned according to the recommended lateral positioning for the section.

Texture

Raw data from a Selcom 2208 32 kHz optocator were obtained along the right wheel track, situated 75 cm to the right of the vehicle's centre line, as recommended for lateral placement. Additionally, a pulse transducer was employed to align the measurements in the longitudinal direction. The reference device, VTI-PTT (Portable Texture Tester), operates as a hand-pushed trolley, as illustrated in Figure 7.

The texture profile used for calculating Megatexture was acquired with a profilometer (Figure 8) at an interval of dx = 0.9 mm, maintaining the same lateral position applied for macrotexture measurements.

Figure 7 Reference equipment VTI-PTT for macrotexture profile measurements. Photo: Linda Corper, VTI.

Figure 8 Reference equipment VTI-MRP for Megatexture. Photo Nicklas Mattisson, VTI.

Hilliness

Every 4 meters along the road's center in the proposed lateral position, a total station records height data, forming a relative profile.

Positioning

Vehicle position

A total station was used to measure points at 20 m intervals along the proposed lateral position in the center of the road. The total station locations were georeferenced using a GPS receiver with RINEX corrections. The same approach was applied to measure the reference points for,

- lane width,
- objects,
- wide transverse profile.

Wide transverse profile

The wide transverse profile was assessed by measuring its endpoints with a total station, while the section between these endpoints was supplemented using the Primal. This gives a six meter wide transverse profile with a profile value every 4 mm, the same set-up as used for assessing the longitudinal reference profile.

Object position

The cones were positioned adjacent to one of the test sections, with some placed near the lane and others at varying distances. Reference measurements were conducted using the same method previously applied under "Vehicle position." The coordinates (X, Y, and Z) indicated the center location at the top of each cone as the reference. A total of five objects were utilized in this setup.

Lane width

Lane width detection was evaluated on a section where temporary yellow tape markings were placed at four points, each simulating a different lane width, see *Figure 9*.

Figure 9 Temporary road marking used to define lane width. Photo: Thomas Lundberg, VTI.

Each segment of road marking measured approximately 18.75 meters in length. Using the total station, the inner position of the road marking was recorded at four distinct points, spaced every 6 meters, along each segment, as illustrated in *Figure 9*.

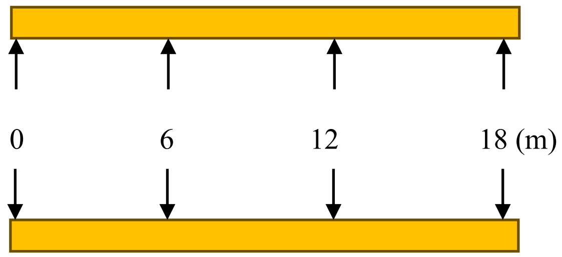


Figure 10 Eight measurement points for defining lane width.

Cracks

The reference for crack measurement involved an in-office assessment of images from the crack section (see *Figure 11*). Each image pixel corresponds to a 1×1 mm area. A 3.8 m wide section was partitioned into 100 mm squares across five zones. Any square containing a crack was marked as activated. The percentage of activated squares within each 20 m segment per zone served as the reference metric.

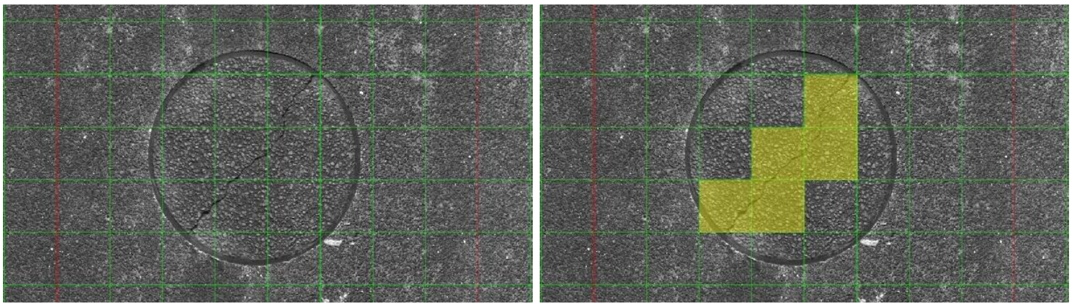


Figure 11 The in-office crack evaluation software. One 100 mm square is activated for the crack at the right side of the picture.

The zones were defined as follows:

Zone 1	0 m – 0.7 m (0 indicating the left side of the road, closest to road middle)
Zone 2	0.7 m – 1.5 m
Zone 3	1.5 m – 2.3 m
Zone 4	2.3 m – 3.1 m
Zone 5	3.1 m – 3.8 m

5.3.2. Supplier measurements

Participants were instructed to cover all sections in a single loop. Each participant completed at least eight repetitions per measurement sequence, using two measurement speeds: 30 and 40 km/h. The driver was instructed to maintain a lateral position at the sections corresponding to where the reference data was collected. To facilitate this, a guideline was marked on the road surface at section A (see Figure 12). At the remaining three sections, the driver was directed to centre the vehicle within the lane, as the width of the lane was relatively narrow.

Figure 12 Reflective tape at the start of section A and the guideline for transverse assistance for the driver. Photo: Nicklas Mattisson, VTI.

The start of each section was defined with a trigger to ensure a good synchronization between the reference data and the data from the tested vehicle. Some systems used photocell and reflector to accomplish this. The reflector (reflective tape) was placed on the pavement (see Figure 12) at the start and end of each section and the trigger signal from the photocell is used to identify the start and stop of the sections in the data stream. Other methods with equivalent accuracy could be used. The measurement sequence was done in the following order, section C, D, A and B.

The measurements were carried out during 5 days, with a total of 26 tested systems. The measurements were conducted between October 9 and October 15, with a break during the weekend. Originally there were 28 systems registered for doing the test, but some gave a late cancellation, and some could not deliver the data because of other circumstances.

The participant could choose to deliver one or more variables from the measurement.

An additional test case was the “stop-and-go” functionality. This situation simulates a temporary stop during a measurement. One section was selected where the operators were instructed to start at normal speed and at a certain point of the section stop the vehicle and accelerate to a normal speed again. As the maximum speed of the test was 40 km/h the speed variation was limited.

The identity of the participants will not be revealed. Each participant was assigned a code (a capital letter). Only the participant has this information, no one else. Chapter 8 gives information about which letter belongs to which system type.

The variables that could be delivered are described in Table 3.

Table 3 List of variables and TermID used in the test.

TermID	Variable
1287	IRI right wheel track
3010	Longitudinal profile right wheel track
1025	Rut depth (3.2 m)
1035	Sliding wire rut depth (2 m)
3302	MPD right wheel track
3109	Megatexture RMS right
3030	Texture profile right
6000	Transverse profile
3000	Crossfall
1547	Hilliness
3020	WGS84 lat
3021	WGS84 long
3022	WGS84 height
4000	Lane width
4001	Object# (object number)
4100	Position lat
4101	Position long
4102	Position height
4200	Wide transverse profile
3030	Cracks
3800	WLPσ
3801	WLPΔ
3030	Texture profile (raw data) in right wheel track

6. Data processing

The target date for data delivery was 1 December 2024. However, VTI allowed later data delivery. All participants have had the opportunity to review a preliminary evaluation of their results and based on this, were given the chance to submit new data which was then used in the final analysis.

The reference for each variable is calculated with either in-house developed software from VTI or independent third-party software, without any connection to the participants.

6.1. Reference calculations

6.1.1. Validity

There are two sets of references to compare the results from the participants, with dedicated reference measurements as described in chapter 5.3.1, and an average of the participants' results. The reference calculations from the dedicated reference measurements will follow international or European standards when applicable. If no standard is available, the methods used by the Swedish Transport Administration will be used (Trafikverket, 2020).

The second reference is calculated as the average of the supplier results, between the 25th and 75th percentiles for each 20-meter section. This will eliminate the potential outliers.

It was difficult to achieve the correct measurement speed at some sections for some participants; this can introduce some disturbance on the longitudinal profile. The longitudinal profile from reference and the participants has therefore been preceded by a high pass filter of 30 meters (3rd order Butterworth forward-reverse) before the analysis. The filtered data is used for the control methods as described in chapters 7.1.3 and 7.2.1. Wavelengths up to 100 meters were used in the Power Spectral Density (PSD) analysis of the longitudinal profiles.

6.1.2. Repeatability

The test of repeatability is done at 20-meter section size. The standard deviation is based on 8 to 10 measurements per participant. The 75th percentile of all 20-meter standard deviations will be used to evaluate repeatability. As a benchmark for the participants the repeatability results are compared with the requirements used in Sweden and/or Finland for this test (see Annex 1).

6.2. Speed dependency

The speed dependency will be presented as the percentage and absolute difference between the average results at speeds of 30 and 40 km/h.

6.3. Reference variables

6.3.1. Longitudinal evenness

The longitudinal reference profile from the Primal has a longitudinal resolution of 4 mm. This profile is transformed to dx=100 mm. The transformed longitudinal profile is used for PSD computation and calculation of the variables IRI and WLP. IRI and WLP are calculated according to EN 13036-5:2019 (CEN, 2019). The PSD was estimated to be using Welch method (Welch, 1967) with a 99% overlap.

6.3.2. Transverse evenness and crossfall

A transverse profile is collected every 0.1 m longitudinally with a sampling interval of 1 mm in the transverse direction. The transverse profile is then filtered. To eliminate edge effects of the filter the raw transverse profile is first mirrored (*Figure 13*). The filtering of the transverse profile has two purposes, to eliminate the effect of the texture and to get rid of noise in the sensor. The raw transverse profile is filtered with a 100 mm three-pole low pass Butterworth filter (forward reverse). After filtering, the middle 3.2 m of the profile is used to represent the reference transverse profile used for calculation of the reference transverse unevenness variables, Rut Depth and crossfall.

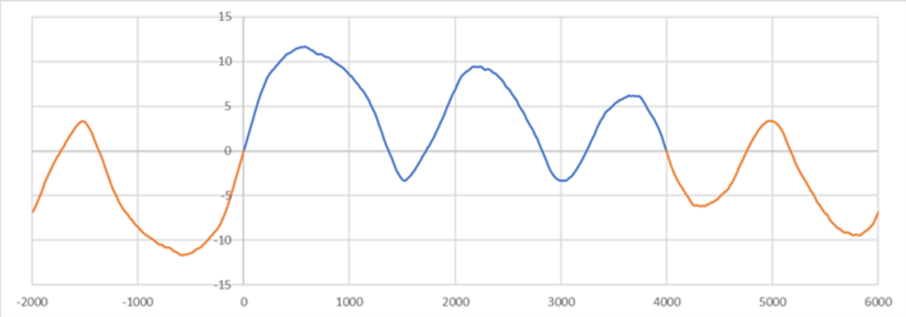


Figure 13 The blue profile is the original profile. The orange expansion is the mirroring.

From the five runs with the reference system, Rut Depth and Crossfall is calculated every 20 meters according to EN 13036-8:2025 (CEN, 2025). The Rut Depth variants used are the total transversal Rut Depth, with a measurement width of 3.2 meters and the 2-meter Sliding Wire Rut Depth. The Crossfall is calculated as the regression slope of the transverse profile, with a measurement width of 3.2 meters (CEN, 2025). The reference is finally established as the average of the three middle values (min and max are excluded), see an example in Table 4. The transverse profile is represented by one of the runs.

Table 4 Example of calculating Rut Depth reference value from five runs. Run1 (min) and 5 (max) (the outliers) are excluded before calculating the average (reference).

Run1	Run2	Run3	Run4	Run5	Average used as reference (average of run 2,3,4)
1.33	1.40	1.45	1.50	2.10	1.45

6.3.3. Texture

The raw data is used to calculate MPD according to ISO 13473-1:2019 (ISO, 2019).

Megatexture is calculated according to ISO 13473-5:2025 (ISO, 2025). Megatexture will be expressed as an RMS-value.

6.3.4. Hilliness

Hilliness is calculated as the average height difference of the 20 m sections. The unit is %. The height difference between the 4-meter readings from the total station are used to calculate the reference hilliness.

Hilliness is expressed as a percentage and calculated for each 20-meter section along the section. The height is measured every 4 meters, which gives five sub-segments per 20 m. For each subsegment, the slope is calculated as height difference divided by horizontal length. The Hilliness for 20 m is then obtained as the average of the five sub-segments, which is mathematically simplified to the total height difference over 20 m divided by 20 m, expressed as a percentage.

Hilliness is calculated as follows (Formula 1).

Let the height be denoted h_k at the distance k meters (where k is 0, 4, 8, 12, 16, 20, ……).

$$H_k = \frac{100}{20}(h_{k+5} - h_k) \qquad (1)$$

6.3.5. Positioning

Vehicle position

The coordinates from the measurements described in chapter 5.3.1 are used to establish the reference. The start of each 20 m section is used to determine the reference. The point at the road surface that corresponds to the middle of the vehicle's ideal transversal position is used as reference. For example, each section has the start distance 0 m and the first delivered 20 m vehicle position of the section has a coordinate from section 0 m, the second delivered vehicle position should be at section 20 m, and so on.

According to the document describing the test[2], the coordinate system could either be DE_DHDN / GK_3 (EPSG:31467) and the heights according to DE_AMST_2016 / NH or WGS84. A more correct coordinate system should have been DE_DHDN / GK_2 (EPSG:31466). The evaluation has been done with DE_DHDN / GK_2. Delivered coordinates in other coordinate systems have been transformed to DE_DHDN / GK_2 using the software gdaltransform from the GDAL project (see gdal.org). The heights from satellite positioning have been delivered in two formats, the orthometric/geoid height according to DE_AMST_2016 / NH and the ellipsoidal height, as given by GNSS receivers. The GNSS heights have been transformed to orthometric height by subtracting 46.624 meters (the difference between geoid and ellipsoid heights at the test site).

6.3.6. Cracks

The reference for cracks was determined from high resolution pictures, see the upper part of Figure 14. To analyze the crack percentage an overlay mask with 0.1 m squares covering a width of 3.8 meters is attached. The surface is divided into 5 lateral zones,

- zone 1 and 5, 0.7 meters
- zone 2, 3 and 4, 0,8 meters.

[2] "DuraBASt test version 3.6.pdf" (not published) describes the test procedures and was sent to the participants prior to the test.

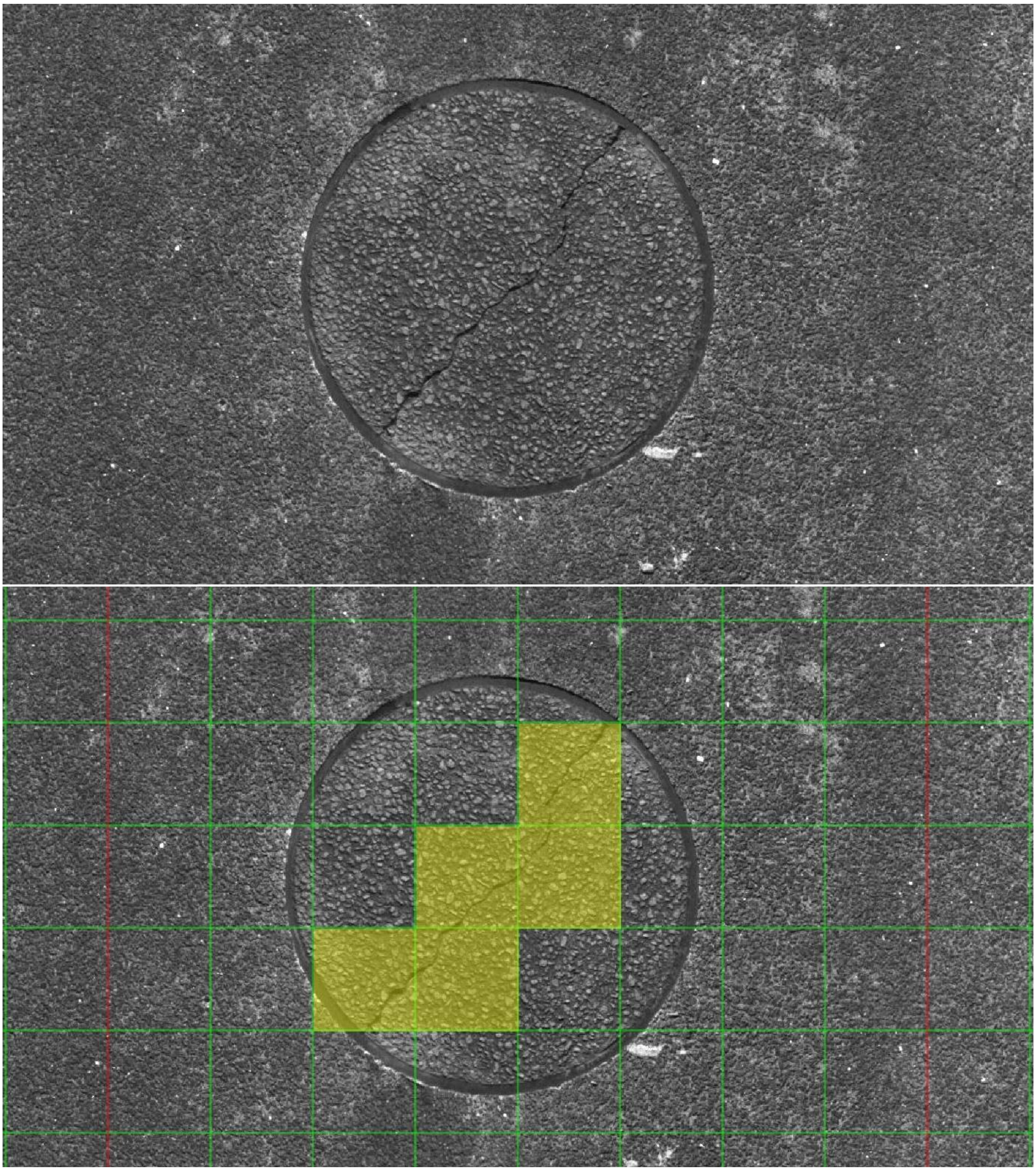


Figure 14 Above, high resolution picture for manual in-office crack detection. Below, manually registered 0.1 m squares with cracks.

All 0.1 m squares with a crack are manually registered, see the yellow squares in the lower part of Figure 14. The crack reference measure is calculated as the percentage of registered 0.1 m squares per zone at 20 m section length.

In this test an average of the percentage cracked surface for all zones is analyzed.

6.3.7. Wide transverse profile

The wide transverse profile should be 6,5 m and be described by 66 data points in the same coordinate system as described in chapter 6.3.5. The distance between each data point should be 0.1 meter. There is a total of five wide transverse profiles, at predetermined sections (from the start of section D) 120 m, 130 m, 140 m, 180 m and 190 m.

6.3.8. Position of objects

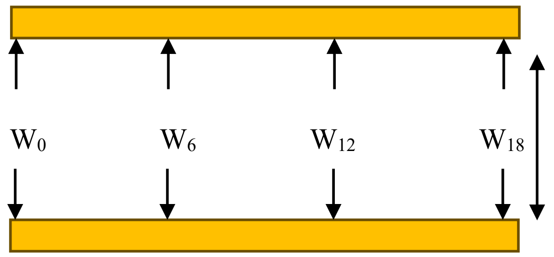
The centre of the cone top is positioned in the same coordinate system as described in chapter 6.3.5. A total of five cones should be positioned. The cones were placed close to section D, according to Table 5.

Table 5 The arrangement of the objects/cones.

Cone#	Distance from start (m)	Transverse distance from road centre (m)	Left/right side
Cone 1	29.5	14.5	Left
Cone 2	66.6	6.4	Right
Cone 3	109.8	2.7	Right
Cone 4	125.5	10	Left
Cone 5	150	13.7	Left

6.3.9. Lane width detection

The average distance between the readings with the total station at the inner side of the road markings is used as the reference lane width. This is done separately for the four road markings. The lane width is calculated as the average of the four individual measurements per set of road markings, according to Figure 15.



Lane width = $(W_0 + W_6 + W_{12} + W_{18})/4$ (m)
W_0 denotes the width at section 0 m.

Figure 15. One set of road markings defining lane width.

6.4. Corrections of obvious errors

Easily explained errors have been detected and corrected in the analysis process. One example is that a few participants got a deviation between the positioning data and the reference that was very close to 20 m. The specifications said that the starting point of every 20 m section should be positioned, but in this case the end point was positioned by the participant. Other examples that have been corrected are longitudinal out-of-sync for a delivered variable. This means that a longitudinal lag between the delivered participant data and the reference was corrected, but only if the correction gave better agreement with reference and higher validity rankings. The possible longitudinal correction was 20 meters, despite some corrections needing only 5 to 15 meters.

7. Analysis methods

The test will be divided into three parts, further described in this chapter.

7.1. Validity

The validity is tested by comparing the results from the tested vehicles with reference values. Two references will be used, as described in chapter 6.1.1. The validity is tested by deciding the percentage of the difference between the tested vehicle and the reference that falls within a given interval, see Figure 16. The interval is described by the funnel shaped black lines in the figure. The normal behavior of a measurement variable is that low measurement values have low standard deviation and vice versa for high measurement values, that's why the interval has the funnel shaped appearance.

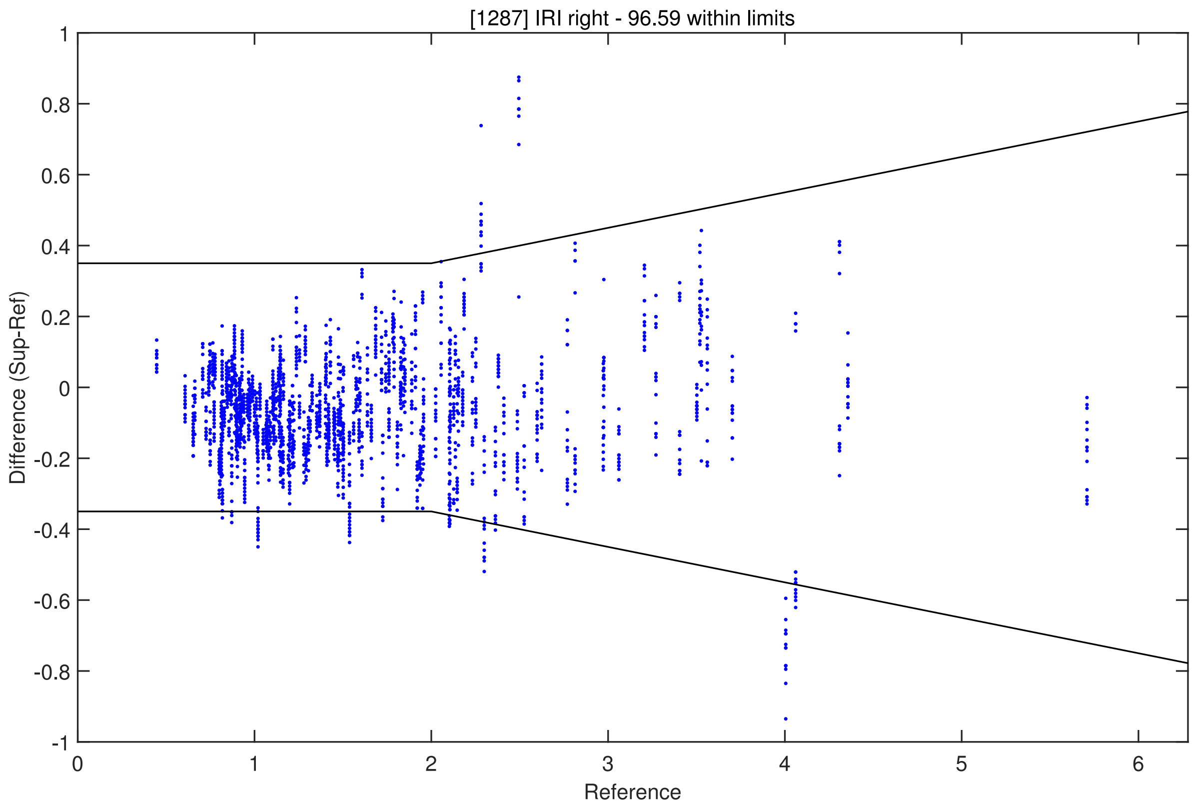


Figure 16 Principles for evaluation of validity. Y axis describes the difference between the tested vehicle and the reference. X axis is the reference value. The result is summarized by the percentage of the difference within the interval.

Two intervals are used in the evaluation. The first interval is copied from the Swedish Transport Administrations technical document (Trafikverket, 2015) additionally some intervals are also used in Finland, that have a similar test methodology. The second interval is wider, adapted to fit connected vehicles and smartphone solutions. For variables without known test limits), the intervals have been experimentally decided or transformed from similar variables using the same source data.

The standard and additional threshold levels can be seen in Annex 1.

7.1.1. Position

The first 100 m of the test sections are used to decide the validity of the measured position. The position is tested by calculating the difference between the tested vehicle and the reference. This is done by calculating the length of the straight line between the reference and participants coordinates for latitude and longitude. The results are presented in a figure showing absolute agreement in the centre of the plot, see Figure 17. There has been some confusion regarding which coordinate system to use. The original plan was to use DE_DHDN / GK_3. Participants and the consultant that did the reference measurements pointed out that it is more correct to use DE_DHDN / GK_2 for the location of duraBASt. Because of this, the analysis was done in the latter format. The participants who delivered position data in other coordinate formats were converted to DE_DHDN / GK_2.

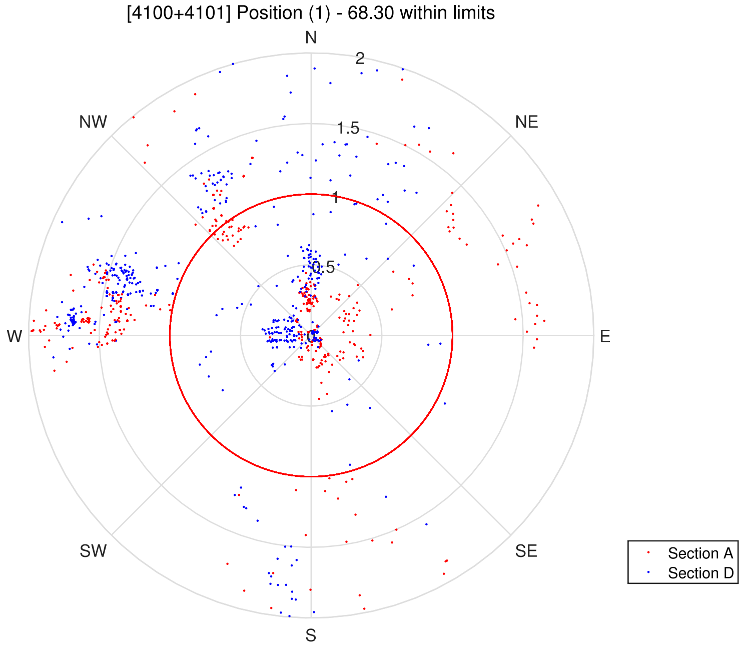


Figure 17 Test principle for position. The center of the circle is the reference position. The red circle specifies the threshold. The different colors represent different test sections. Units in meters.

7.1.2. Transverse profile

The transverse profile was not possible to analyze, because the matching routine between the reference and the supplier is based on cross-correlation. The test track has no ruts, and a flat profile gives no possibility to get a valid transverse matching between the transverse profiles from the participant and reference. A typical example is given in Figure 18.

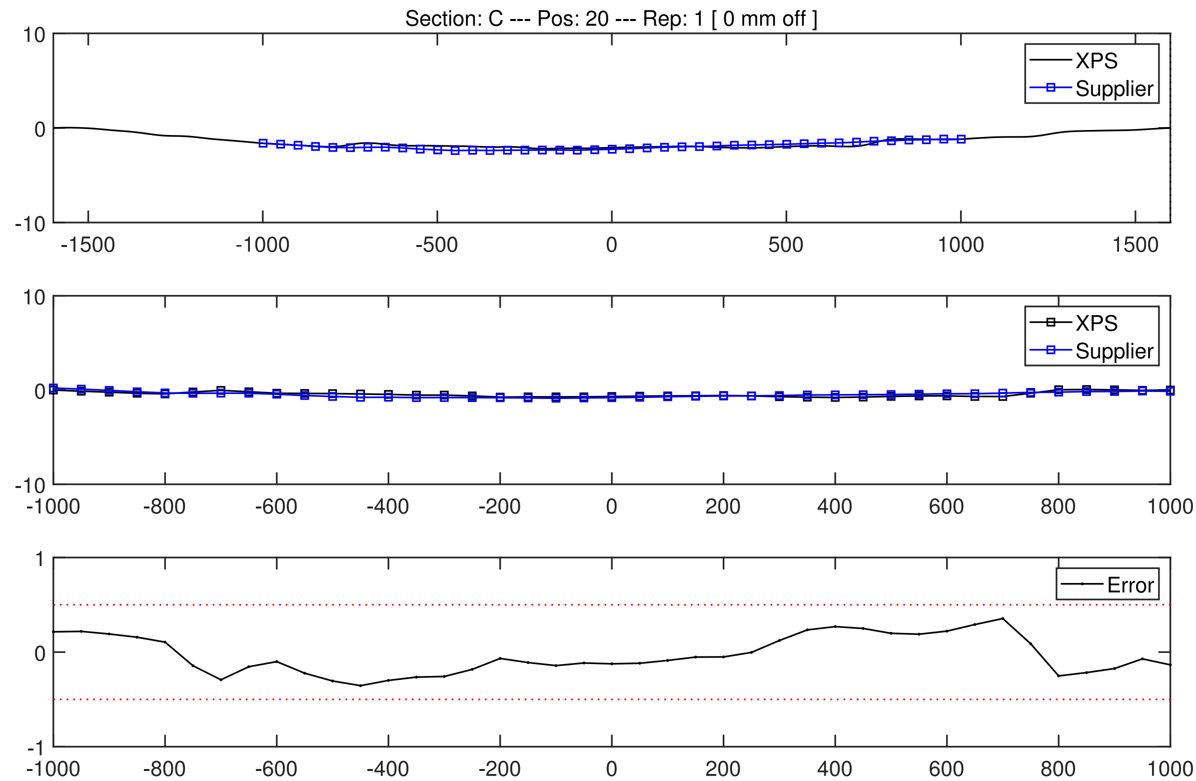


Figure 18 Example of comparison between reference and supplier transversal profile. Units, X and Y in mm.

7.1.3. Longitudinal profile

The longitudinal profiles are preprocessed according to chapter 6.1.1.

The longitudinal profile is tested according to the following steps,

- Synchronize the longitudinal profiles from the supplier and reference (cross correlation) (synchronized at 100 mm level).
- The synchronized profiles are compared in two ways.
    - Correlation per 100 m.
    - Quota of the standard deviations per 100 m between the supplier and reference.

Only full 100-m sections are used in the analysis. The results for correlation and the quota test are compared with a threshold level.

Additionally, the frequency content (PSD, Power Spectrum Density) is compared between the reference and the tested vehicle. This will show the agreement between the reference and the tested vehicle through the entire frequency spectra for evenness. The PSD test will be limited to wavelengths between 0.2 and 100 meters.

7.2. Repeatability

The 75th percentile of the standard deviation of the repeated runs for 20-meter values is used as a metric for repeatability.

7.2.1. Longitudinal profile

The longitudinal profiles are preprocessed according to chapter 6.1.1.

The longitudinal profile is tested according to the following steps:

- Synchronize the longitudinal profiles from the suppliers' repetitions at 100 mm level (cross correlation).
- All combinations of the repeated synchronized profiles are compared in two ways.
    - Correlation per 100 m.
    - Quota of the standard deviations per 100 m between the supplier and reference.
- The results are checked according to requirements for correlation and the quota.

7.3. Speed Dependency

Originally the plan was to have a broader variety of measurement speeds. However, the study will present the quota of the average of the suppliers' measurements in 40 and 30 km/h, even if the span between the speeds is close. Additionally, the absolute value of the average between the results at the two speeds will be reported. Variables that can have a value close to zero (crossfall, hilliness) and very large numbers (the positioning variables) the quota will not be reported.

8. Participant Categories

The report will not reveal the connection between the result and the different measurement systems or participating companies. To be able to get information about how different measurement principles perform in this test, the measurement systems are divided into three categories describing the main measurement principle. The participating systems are divided into the three categories according to Table 6. The three categories are:

1. Profilometer – the traditional type of road surface monitoring systems equipped with laser-based measuring techniques, point lasers or line lasers. Several systems also have the capability to measure and capture road vicinity with Lidar systems and 360-cameras.
2. Mobile mapping system – the main data source is the Lidar-type equipment that is used to describe the road surface and vicinity in detail, often combined with 360-cameras. Some systems also have point lasers as a complement to the Lidars. The point lasers are used for texture and in some cases evenness measurements. To distinguish the systems using both Lidar and point laser from the profilometer category, this category uses the Lidar technique to measure the transverse profile.
3. Connected vehicle and smartphone solution – this category includes connected vehicle type of data supplier, using the sensors in the vehicle to estimate the condition of the road. Also, smartphone solutions collecting data with a smartphone, sometimes using extra gauges connected to the smartphone. The third system belonging to this group is vehicle response measuring systems, a vehicle equipped with extra gauges connected to a laptop, measuring the response of the vehicle to estimate the road condition.

Table 6 Participating systems and their respective categories.

Category	Measurement system	Comments
Profilometers	B I J L M O Q R S T	If the measuring method used to assess the transverse profile is done with a point laser or a line laser the system will be in this category.
Mobile mapping systems Mobile mapping systems	D E H K P U Y Z	If the measuring method used to assess the transverse profile is done with a Lidar system, the system will be in this category, even if the system could have point lasers to measure evenness and texture.
Connected vehicles and smartphone solutions	A N V	It should be noted that this category measures the vehicle response (evenness) not only in one wheel path. The reference is

Category	Measurement system	Comments
	W X	calculated from the right wheel path. The test track is, however, built homogenous, meaning there are very small differences between the two wheel paths.

9. Results

The results will be detailed in individual chapters addressing validity, repeatability, and speed dependency. Furthermore, both the PSD evaluation and the quality control of longitudinal profiles will be covered separately. The report will also provide an evaluation of wide transverse profile measurements, object positioning, and lane width determination.

Variable testing outcomes will be compared against standard requirements in Sweden and Finland, where this procedure is integral to the technical approval process managed by the Transport Administrations for network road monitoring service procurement. The requirements are only for information, it's by no means a requirement in this test. The primary objective of the Transport Administration, by using these requirements, is to ensure a consistent, long-term trend to support effective and accurate maintenance planning.

The following abbreviations will be used,

Ref dedicated reference measurement

Sys_ref participating system reference

Prof or P the category profilometer

MM or M the category mobile mapping

CV or C the category connected vehicle and smartphone solution

s standard deviation (s_Prof, the standard deviation for profilometers)

To get a representative value for a system category, obvious measurement errors are excluded from the system average and system standard deviation when comparing different system types.

9.1. Validity

This chapter outlines the validity results. The data shown represents aggregated information for both participants and system categories. A comprehensive report for each participant is available in Annex 2. The diagrams present a comparison using 20 m data from all test sections relevant to each variable. The table below details the applicable sections corresponding to each tested variable.

Table 7 Explanation of the sections utilized to examine the validity of the variables.

Section/TermID-description	1287, 1025, 1035, 3000, 3800, 3801	3302, 3109	4100, 4101, 4102	Lane width, Object position, Wide transverse profiles	Cracks
A	0-240 m	0-240 m	0-100 m		
B					X
C	0-180 m				
D	0-260 m	0-260 m	0-100 m	X	

9.1.1. TermID 1287 – IRI right wheel track

IRI reference is evaluated in the right wheel track. The two references used are dedicated reference measurement and the system average. In total, 21 systems reported IRI data.

Initially, results from participants are compared to the references. This comparison follows the procedures outlined in chapter 7.1, using threshold levels specified in Annex 1. The comparison is performed for each subsection, at 20 m interval, and each repetition. For example, as shown in Table 8, System B achieved 57.8% within limit 1 according to the dedicated reference measurements. The results are divided into two tables, comparison with reference (Table 8) and system reference (Table 9).

Table 8 Validity of participants results for IRI in right wheel track compared with reference measurement.

System	Category	Validity_Ref1	Validity_Ref2	Requirement
B	P	57.8%	89.2%	75%
J	P	82.3%	88.9%	75%
L	P	39.2%	54.9%	75%
M	P	87.8%	94.4%	75%
O	P	59.4%	86.5%	75%
Q	P	32.6%	51.7%	75%
R	P	82.5%	93.6%	75%
S	P	70.5%	92.0%	75%
D	MM	85.1%	94.6%	75%
E	MM	88.9%	94.7%	75%
H	MM	50.4%	66.4%	75%
K	MM	94.2%	94.4%	75%
P	MM	31.3%	57.6%	75%
U	MM	80.0%	88.6%	75%
Y	MM	75.3%	93.2%	75%
Z	MM	65.3%	84.2%	75%
A	CV	23.2%	34.7%	75%
N	CV	39.2%	55.3%	75%
W	CV	38.1%	67.4%	75%
X	CV	73.8%	88.3%	75%

Table 9 Validity of participants results for IRI in right wheel track compared with system reference.

System	Category	Validity_Sysref1	Validity_Sysref2	Requirement
B	P	77.5	96.9	75%
J	P	93.4	94.4	75%
L	P	37.2	53.1	75%
M	P	91.7	100.0	75%
O	P	83.3	93.8	75%
Q	P	39.6	56.3	75%
R	P	95.6	100.0	75%
S	P	86.1	96.9	75%

System	Category	Validity_Sysref1	Validity_Sysref2	Requirement
D	MM	91.7	99.1	75%
E	MM	93.7	99.5	75%
H	MM	56.4	75.4	75%
K	MM	96.1	100.0	75%
P	MM	38.9	71.9	75%
U	MM	82.9	94.3	75%
Y	MM	89.5	97.2	75%
Z	MM	54.2	80.0	75%
A	CV	22.7	33.0	75%
N	CV	40.3	56.4	75%
W	CV	55.2	81.7	75%
X	CV	79.6	90.7	75%

It is unsurprising that the participants' results align more closely with the system's reference than with the dedicated reference measurement.

The average and standard deviation of IRI in right wheel track for system categories and reference is presented in Figure 19.

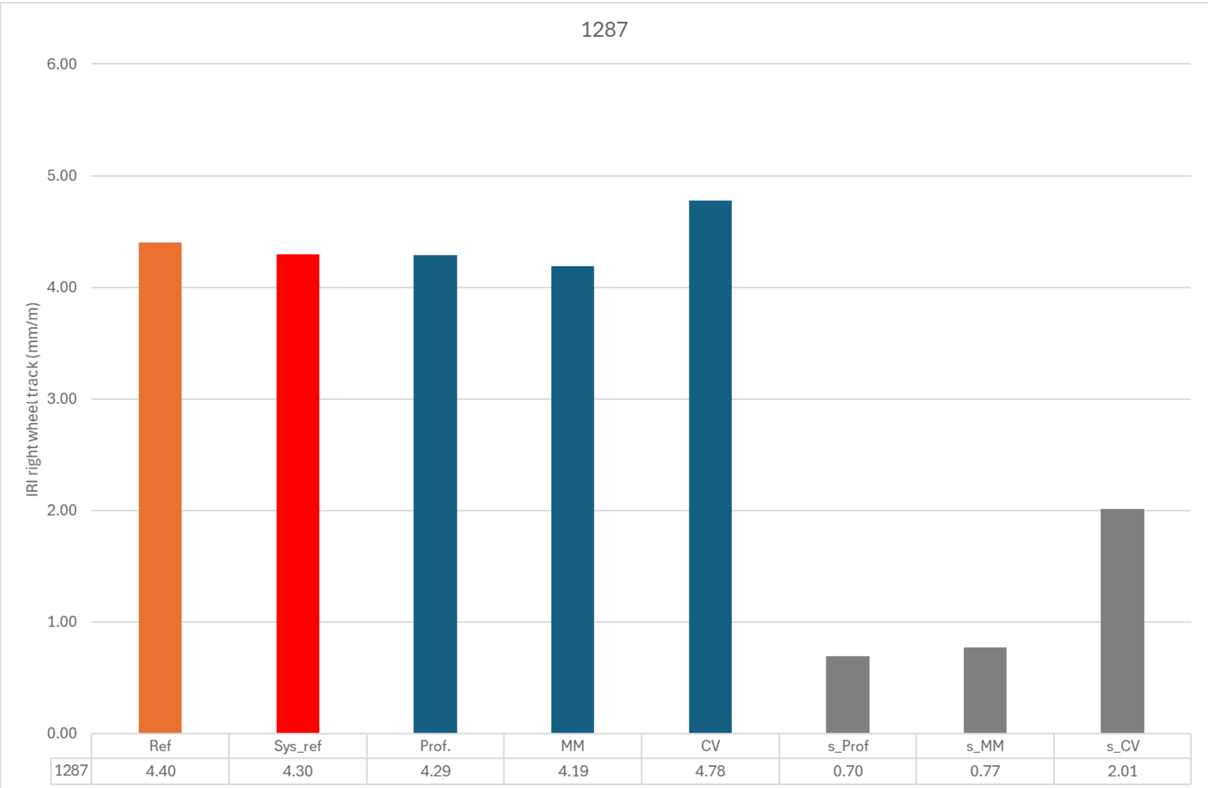


Figure 19 Overall average and standard deviation of IRI in right wheel track.

A more detailed comparison, with data at 20 m section size, between the references and the average of the repeated runs for the participant categories can be seen in Figure 20. The following figures, Figure

20 through Figure 23, are marked with black vertical lines to indicate the end and start of a test section. For IRI, the relevant sections are A, C, and D.

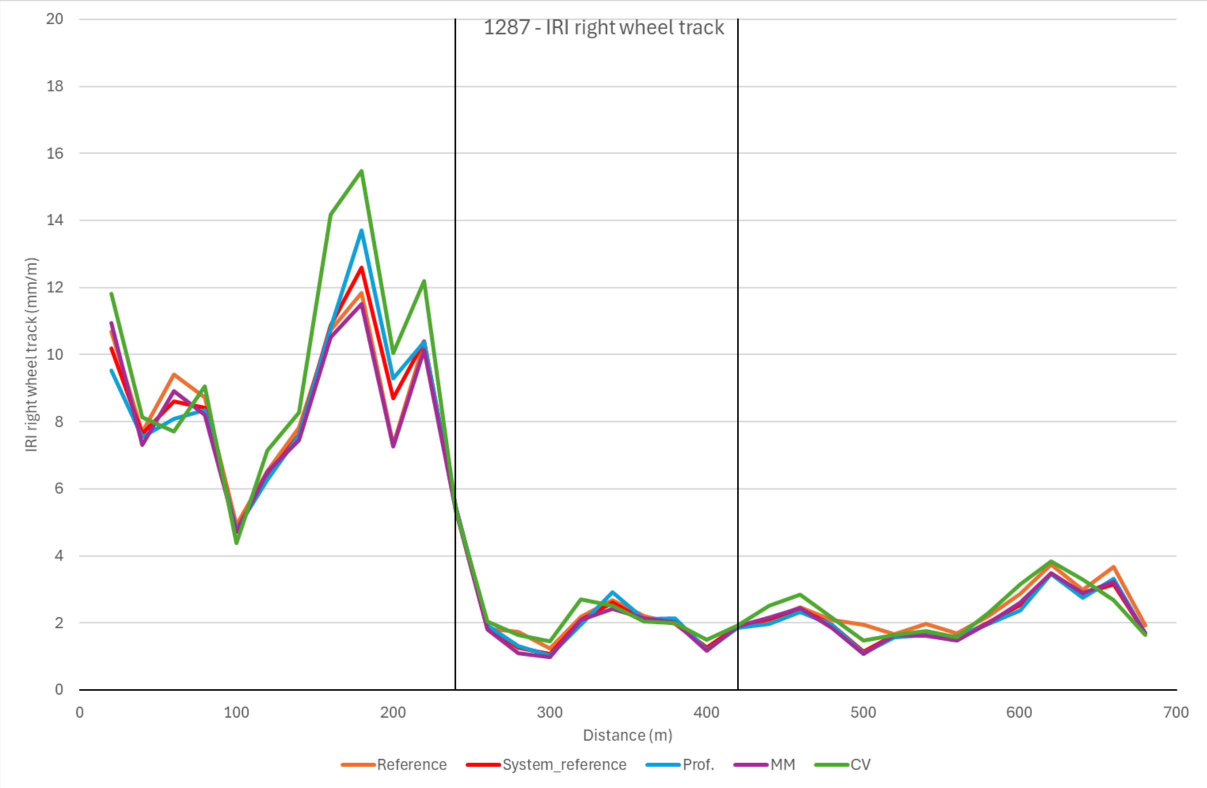


Figure 20 IRI, 20 m comparison between references and the average of the three participant categories.

The individual participants' average results for the three categories compared with the references can be seen in Figure 21 to Figure 23.

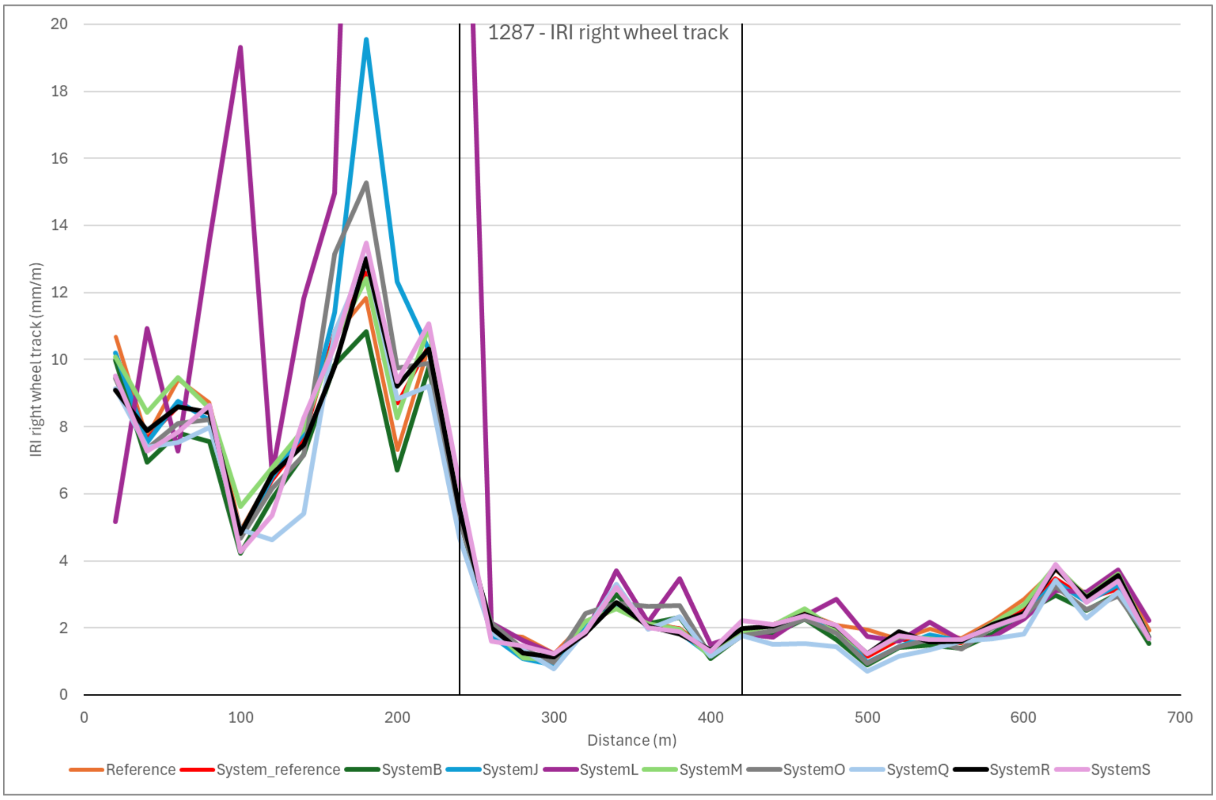


Figure 21 IRI: comparison of reference values with each participant's average in the profilometer category.

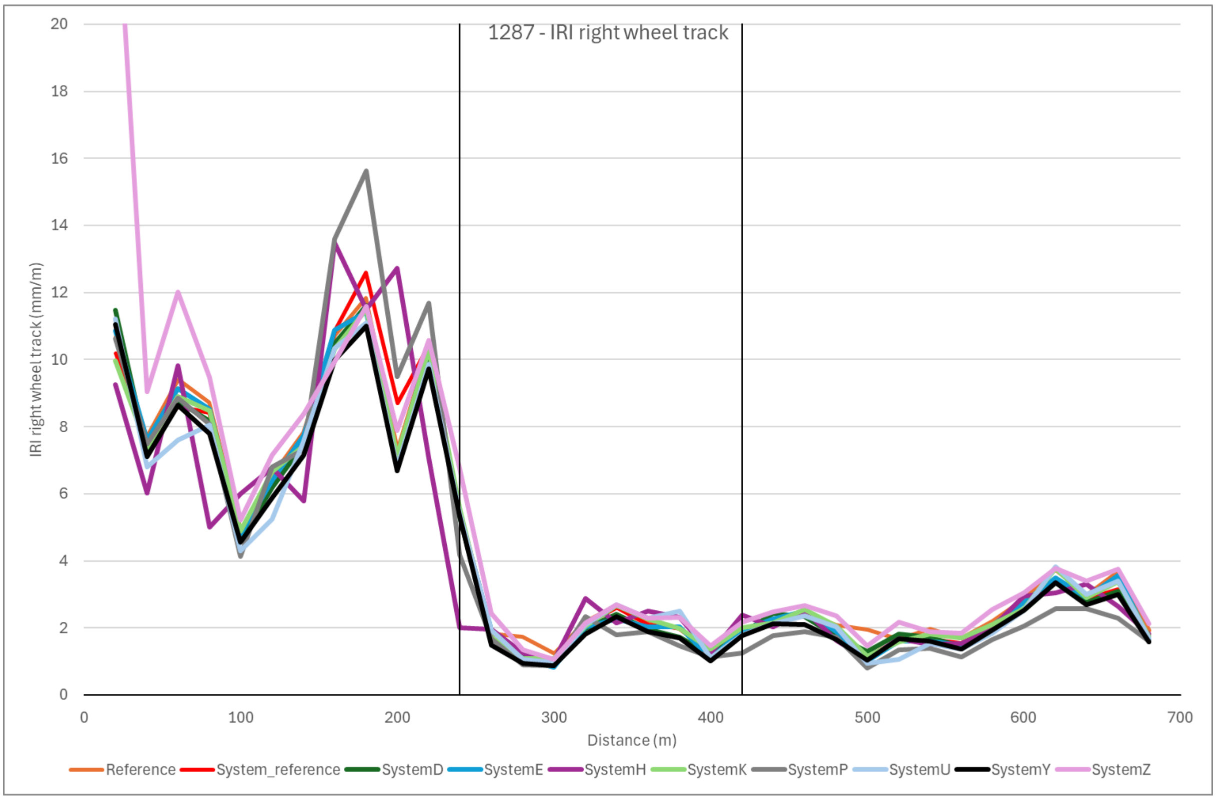


Figure 22 IRI: comparison of reference values with each participant's average in the mobile mapping category.

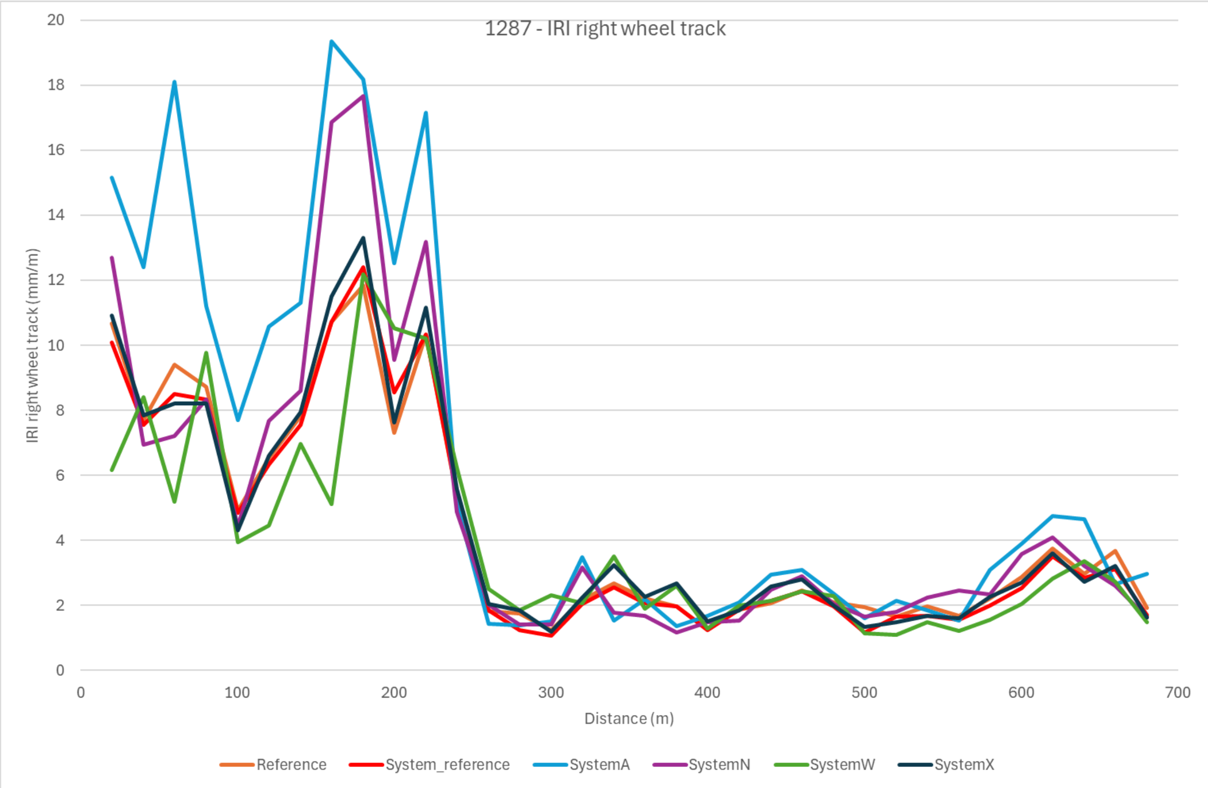


Figure 23 IRI: comparison of reference values with each participant's average in the connected vehicle category.

9.1.2. TermID 1025 – Rut Depth 3.2 m

The Rut Depth 3.2 m reference is calculated from the reference transverse profile for a width of 3.2 m, based on the predetermined lateral position. Each participant uses a reference tailored to the measurement point configuration of their specific system, resulting in different references between suppliers. Consequently, the diagrams display both the minimum and maximum reference values for the Rut Depth. The two references utilized are a dedicated reference measurement and the system average. A total of 13 systems provided Rut Depth 3.2 m data.

Initially, results from participants are compared to the references. This comparison follows the procedures outlined in chapter 7.1, using threshold levels specified in Annex 1. The comparison is performed for each subsection, at 20 m interval, and each repetition. For example, as shown in Table 10, System J achieved 79.9% within limit1 according to the dedicated reference measurements. The results are divided into two tables, comparison with reference (Table 10) and system reference (Table 11.

Table 10 Validity of participants results for Rut Depth 3.2 m compared with reference measurement.

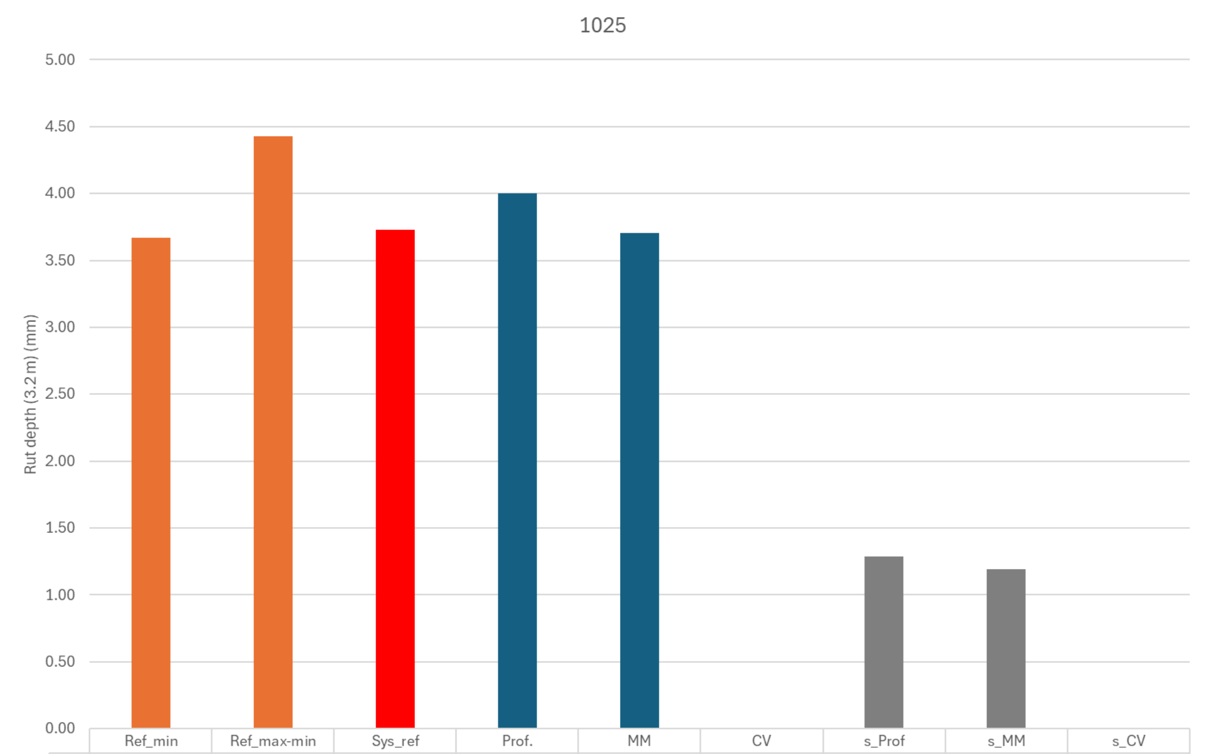
System	Category	Validity_Ref1	Validity_Ref2	Requirement
J	P	79.9%	96.9%	80%
L	P	56.9%	89.9%	80%
M	P	84.4%	100.0%	80%
O	P	76.0%	99.3%	80%
R	P	76.1%	97.2%	80%
S	P	4.9%	44.8%	80%

System	Category	Validity_Ref1	Validity_Ref2	Requirement
D	MM	2.0%	66.3%	80%
E	MM	91.3%	96.1%	80%
H	MM	94.6%	96.8%	80%
K	MM	95.6%	100.0%	80%
P	MM	19.8%	92.4%	80%
U	MM	74.3%	88.6%	80%
Y	MM	1.5%	95.4%	80%

Table 11 Validity of participants results for Rut Depth 3.2 m compared with system reference measurement.

System	Category	Validity_Sysref1	Validity_Sysref2	Requirement
J	P	85.8	97.2	80%
L	P	33.3	79.5	80%
M	P	24.2	98.3	80%
O	P	79.2	91.0	80%
R	P	96.1	97.2	80%
S	P	24.0	85.4	80%
D	MM	35.1	100.0	80%
E	MM	68.6	94.7	80%
H	MM	97.9	99.6	80%
K	MM	90.8	100.0	80%
P	MM	90.6	100.0	80%
U	MM	57.1	82.9	80%
Y	MM	49.4	100.0	80%

The average and standard deviation of Rut Depth 3.2 m for system categories and reference is presented in Figure 24.



	Ref_min	Ref_max-min	Sys_ref	Prof.	MM	CV	s_Prof	s_MM	s_CV
1025	3.67	4.43	3.73	4.00	3.71	0.00	1.29	1.19	0.00

Figure 24 Overall average and standard deviation of Rut Depth 3.2 m.

A more detailed comparison, at 20 m level, between the references and the average of the repeated runs for the participant categories can be seen in Figure 25. The following figures, Figure 25 through Figure 27, are marked with black vertical lines to indicate the end and start of a test section. For Rut Depth, the relevant sections are A, C, and D.

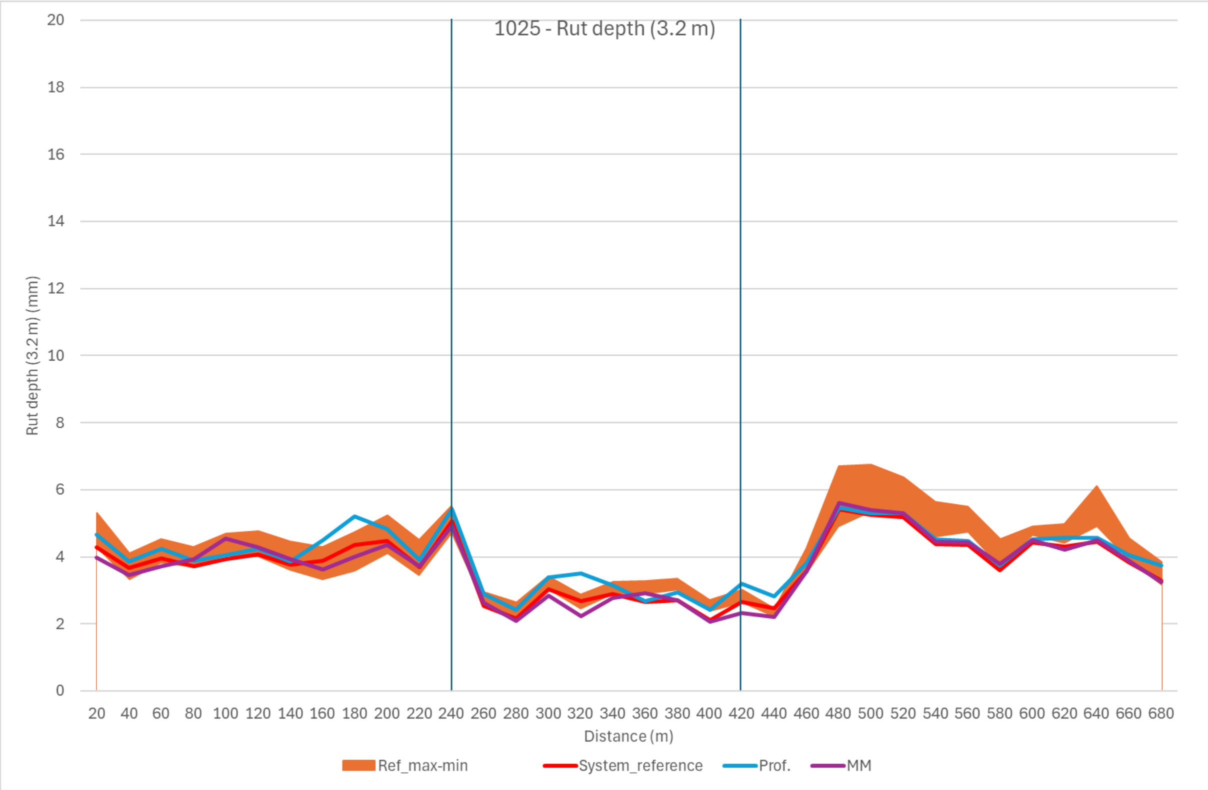


Figure 25 Rut Depth 3.2 m, 20 m comparison between references and the average of the two participant categories.

The individual participants' average results for the two categories compared with the references can be seen in Figure 26 and Figure 27.

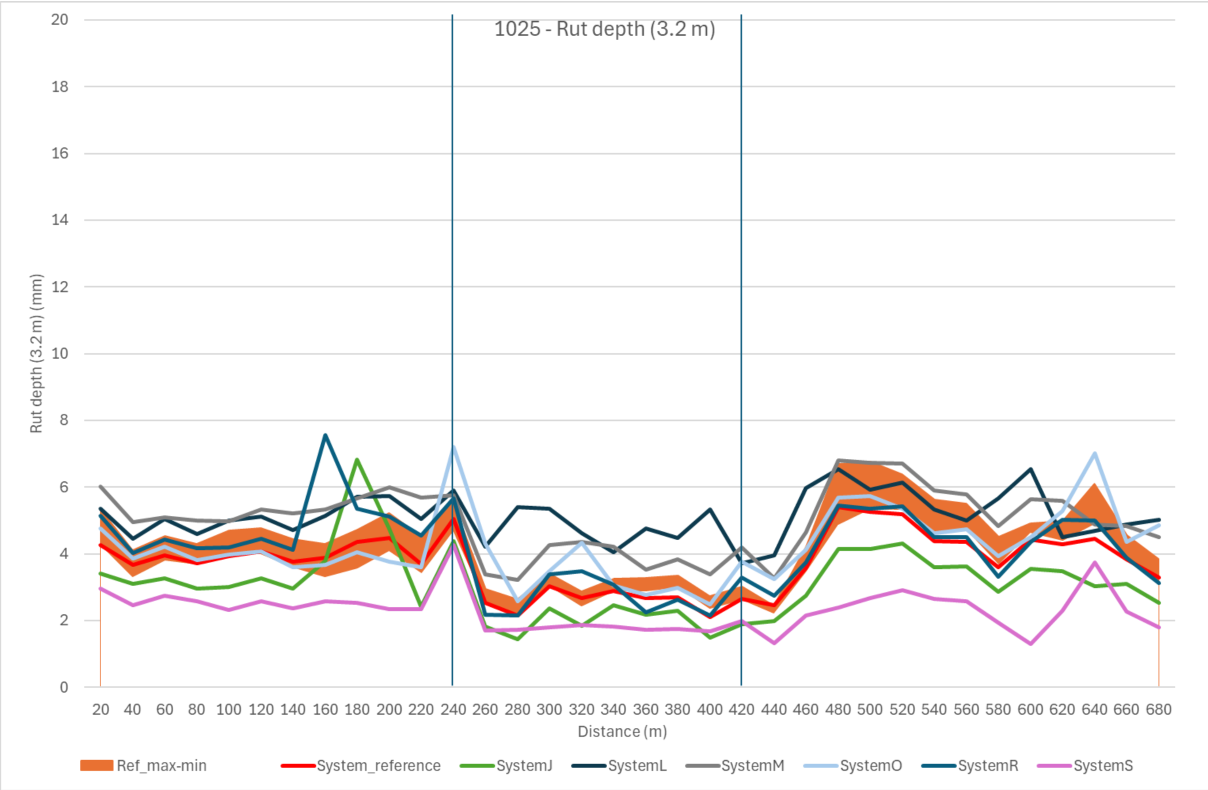


Figure 26 Rut Depth 3.2 m: a comparison between reference values and the average of the measurements obtained by participants in the profilometer category.

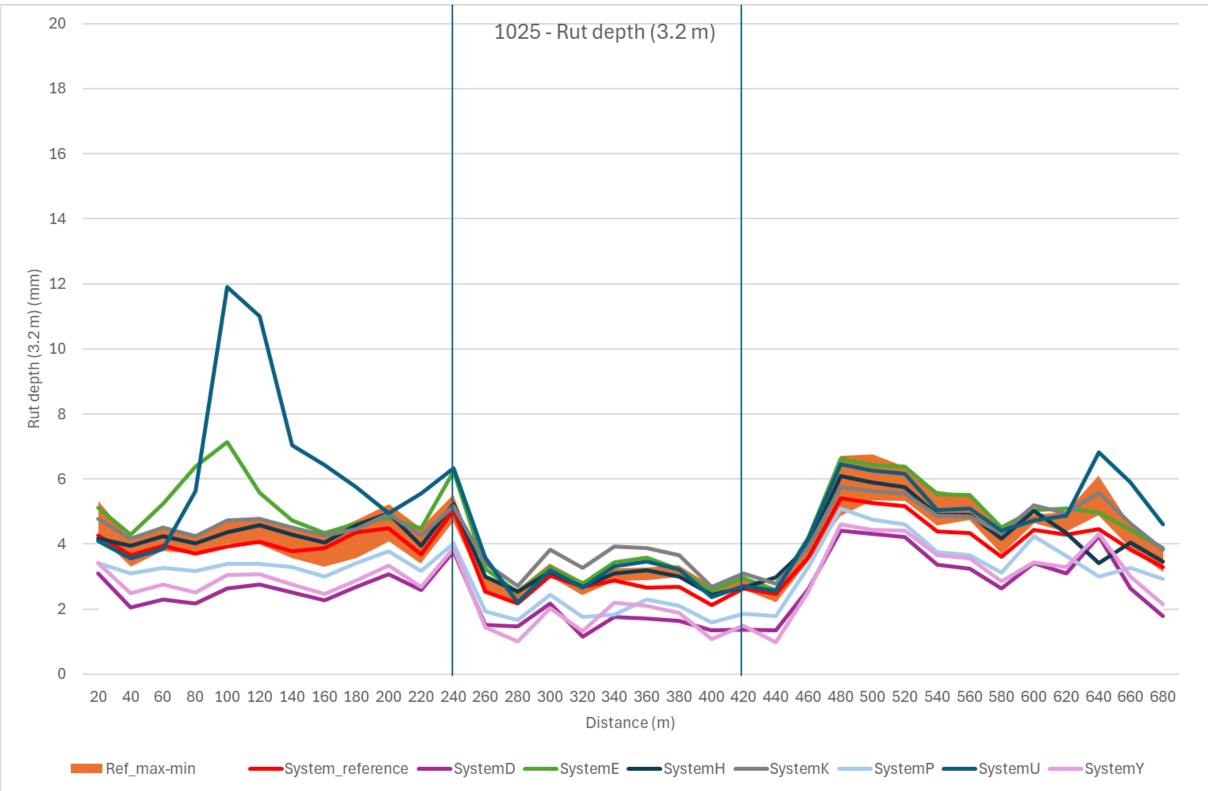


Figure 27 Rut Depth 3.2 m: a comparison between reference values and the average of the measurements obtained by participants in the mobile mapping category.

9.1.3. TermID 1035 – Sliding Wire Rut Depth 2,0 m

The Sliding Wire Rut Depth 2,0 m reference is calculated from the reference transverse profile within a width of 3.2 m, based on the predetermined lateral position. Each participant uses a reference tailored to the measurement point configuration of their specific system, resulting in different references between suppliers. Consequently, the diagrams display both the minimum and maximum reference values for the Sliding Wire Rut Depth. The two references utilized are a dedicated reference measurement and the system average. A total of 10 systems provided Sliding Wire Rut Depth data.

Initially, results from participants are compared to the references. This comparison follows the procedures outlined in chapter 7.1, using threshold levels specified in Annex 1. The comparison is performed for each subsection, at 20 m interval, and each repetition. For example, as shown in Table 12, System L achieved 85.4% within limit1 according to the dedicated reference measurements. The results are divided into two tables, comparison with reference (Table 12) and system reference (Table 13).

Table 12 Validity of participants results for Sliding Wire Rut Depth 2.0 m compared with reference measurement.

System	Category	Validity_Ref1	Validity_Ref2	Requirement
L	P	85.4%	95.1%	80%
M	P	86.1%	98.6%	80%
O	P	49.3%	92.4%	80%
S	P	7.6%	51.0%	80%
D	MM	6.3%	96.6%	80%
E	MM	94.7%	100.0%	80%

System	Category	Validity_Ref1	Validity_Ref2	Requirement
K	MM	98.9%	100.0%	80%
U	MM	71.4%	85.7%	80%
Y	MM	0.9%	97.2%	80%
Z	MM	93.1%	100.0%	80%

Table 13 Validity of participants results for Sliding Wire Rut Depth 2.0 m compared with system reference measurement.

System	Category	Validity_Sysref1	Validity_Sysref2	Requirement
L	P	70.1	94.8	80%
M	P	28.6	89.7	80%
O	P	91.7	100.0	80%
S	P	43.1	84.7	80%
D	MM	82.6	100.0	80%
E	MM	66.2	97.1	80%
K	MM	95.6	100.0	80%
U	MM	45.7	74.3	80%
Y	MM	80.3	100.0	80%
Z	MM	100.0	100.0	80%

The average and standard deviation of Sliding Wire Rut Depth 2.0 m for system categories and reference is presented in Figure 28.

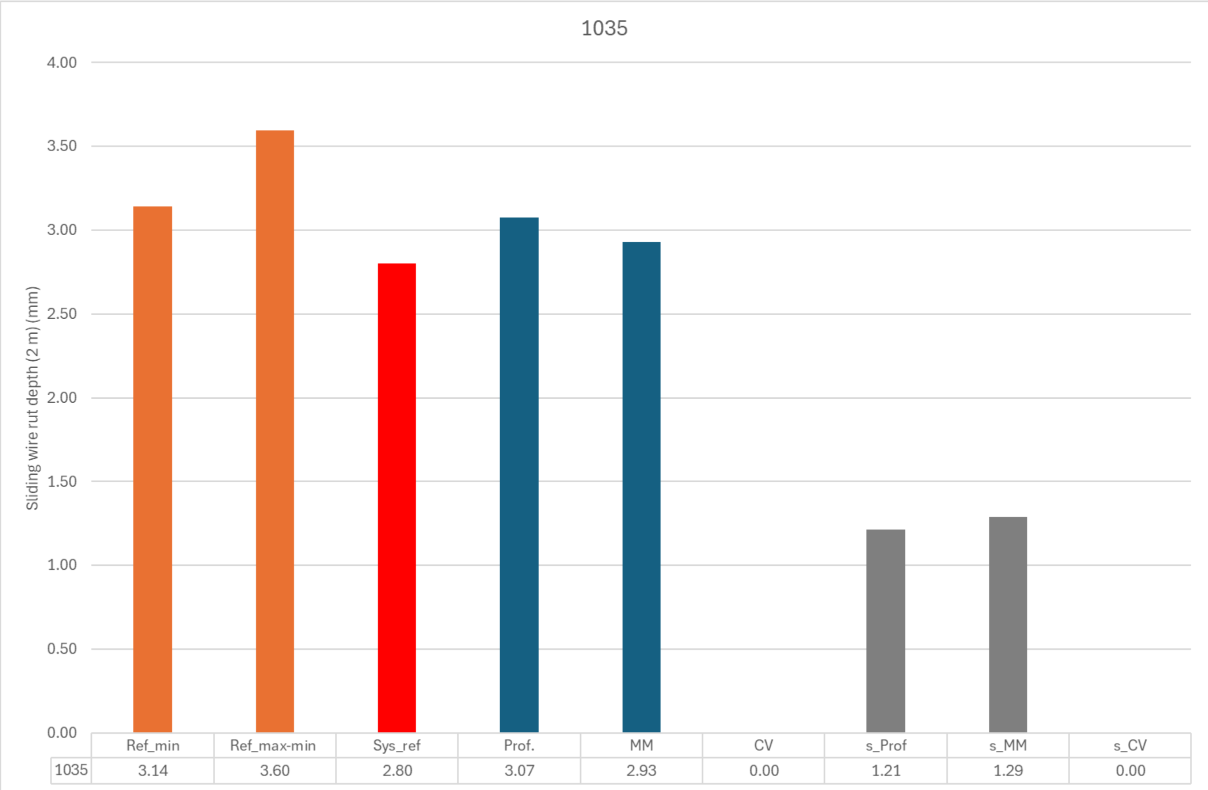


Figure 28 Overall average and standard deviation of Sliding Wire Rut Depth 2.0 m.

A more detailed comparison, at 20 m level, between the references and the average of the repeated runs for the participant categories can be seen in Figure 29. The following figures, Figure 29 through Figure 31, are marked with black vertical lines to indicate the end and start of a test section. For Rut Depth, the relevant sections are A, C, and D.

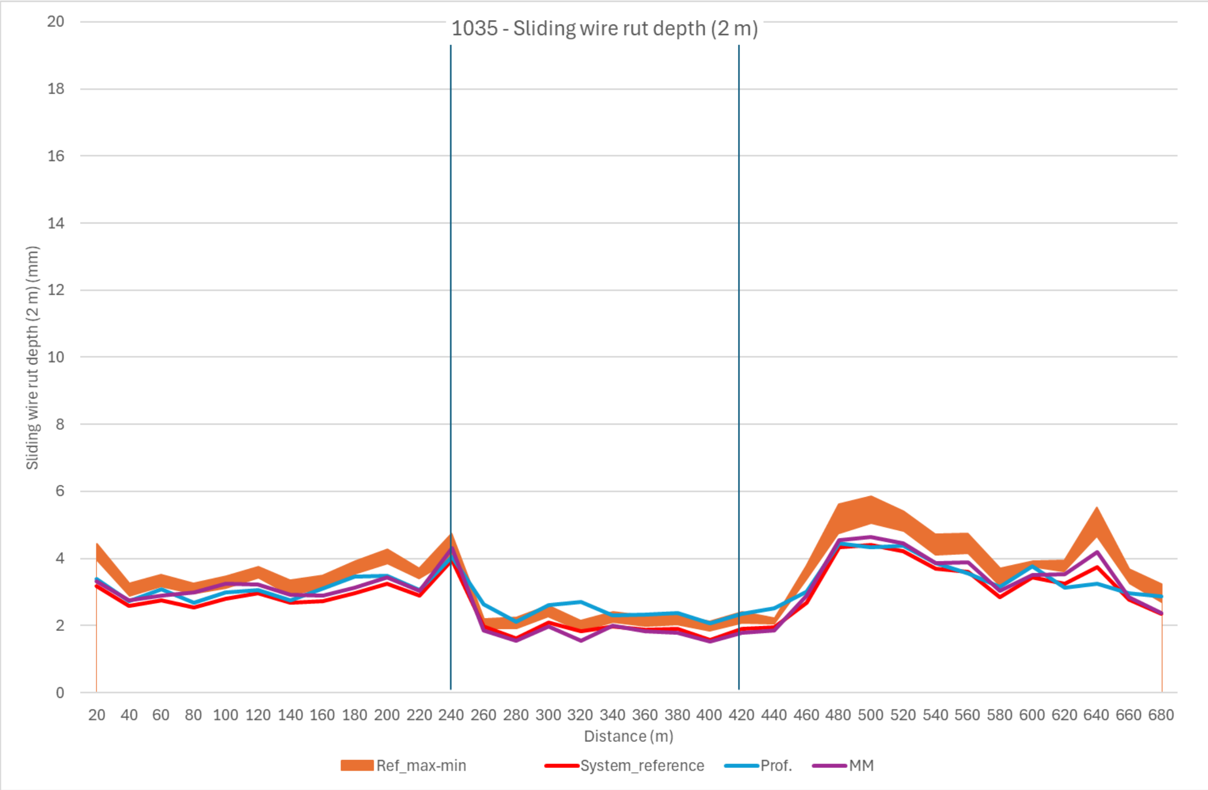


Figure 29 Sliding Wire Rut Depth 2.0 m, 20 m comparison between references and the average of the two participant categories.

The individual participants' average results for the two categories compared with the references can be seen in Figure 30 and Figure 31.

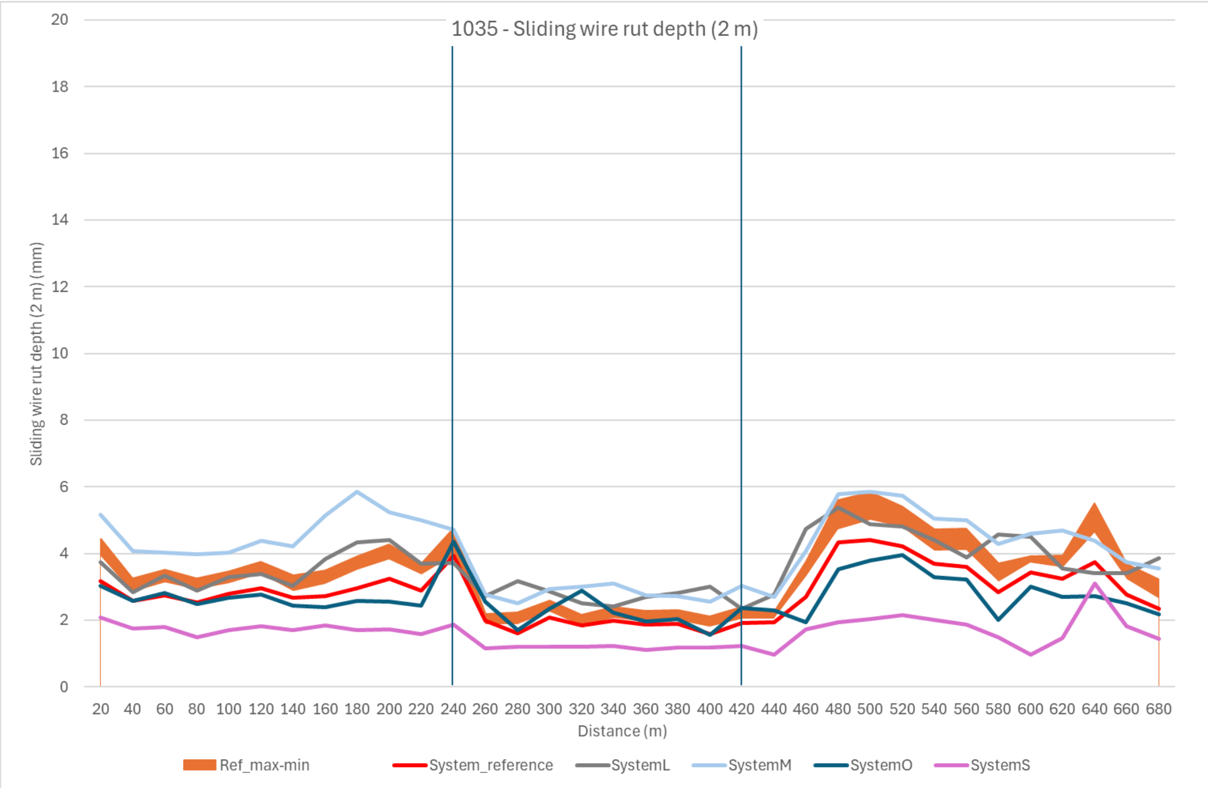


Figure 30 Sliding Wire Rut Depth 2.0 m: a comparison between reference values and the average of the measurements obtained by participants in the profilometer category.

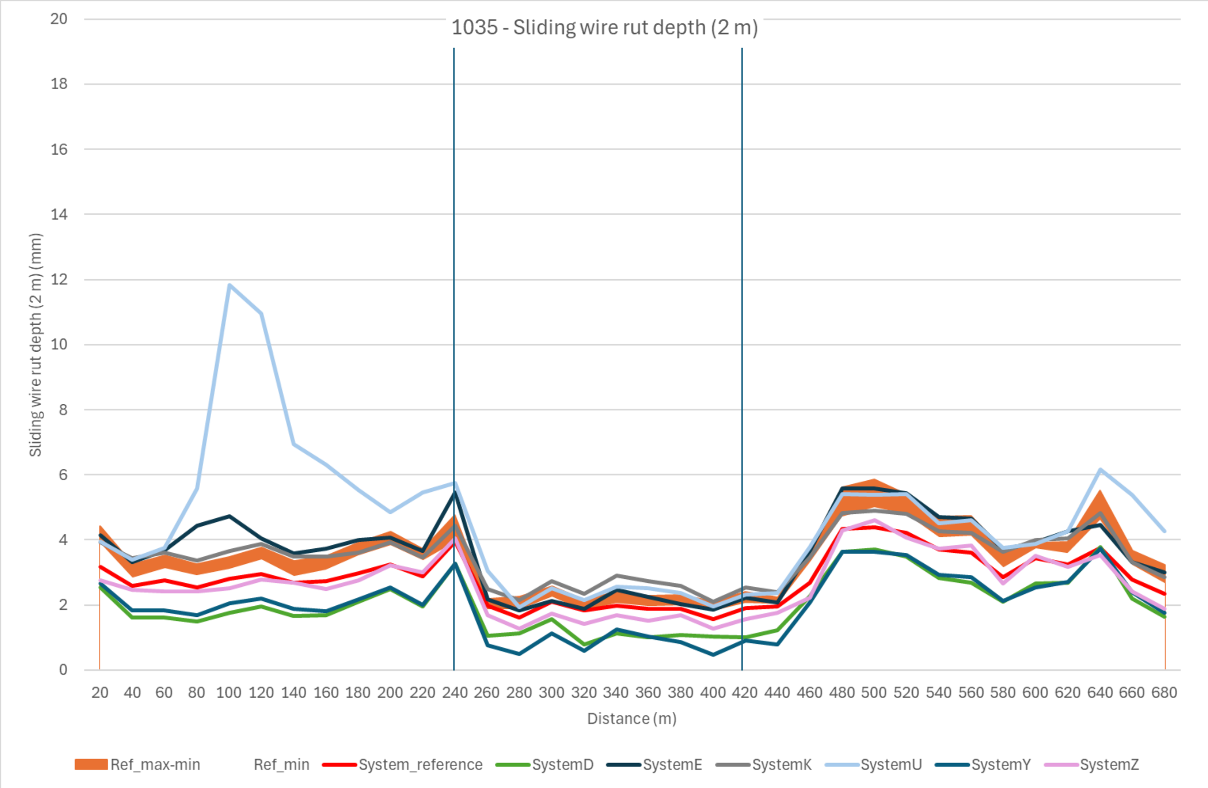


Figure 31 Sliding Wire Rut Depth 2.0 m: a comparison between reference values and the average of the measurements obtained by participants in the mobile mapping category.

9.1.4. TermID 3000 – Crossfall regression 3.2 m

The reference regression crossfall is calculated from the reference transverse profile within a width of 3.2 m in combination with the inertial navigation system, based on the predetermined lateral position. Each participant uses a reference tailored to the measurement point configuration of their specific system, resulting in different references between suppliers. Since the variation between different participants references is low, only one reference will be presented in the diagrams. The two references utilized are a dedicated reference measurement and the system average. A total of 12 systems provided crossfall regression data.

Initially, results from participants are compared to the references. This comparison follows the procedures outlined in chapter 7.1, using threshold levels specified in Annex 1. The comparison is performed for each subsection, at 20 m interval, and each repetition. For example, as shown in Table 14, System L achieved 78.5% within limit1 according to the dedicated reference measurements. The results are divided into two tables, comparison with reference (Table 14) and system reference (Table 15).

Table 14 Validity of participants results for Crossfall regression 3.2 m compared with reference measurement.

System	Category	Validity_Ref1	Validity_Ref2	Requirement
L	P	77.1%	85.8%	85%
M	P	97.2%	100.0%	85%
Q	P	75.7%	84.7%	85%
R	P	100.0%	100.0%	85%
S	P	91.3%	96.9%	85%

System	Category	Validity_Ref1	Validity_Ref2	Requirement
D	MM	100.0%	100.0%	85%
H	MM	100.0%	100.0%	85%
K	MM	97.2%	100.0%	85%
P	MM	94.1%	100.0%	85%
U	MM	100.0%	100.0%	85%
Y	MM	100.0%	100.0%	85%
Z	MM	88.9%	97.2%	85%

Table 15 Validity of participants results for Crossfall regression 3.2 m compared with system reference measurement.

System	Category	Validity_Sysref1	Validity_Sysref2	Requirement
L	P	74.7%	84.4%	85%
M	P	100.0%	100.0%	85%
Q	P	78.5%	84.0%	85%
R	P	100.0%	100.0%	85%
S	P	97.2%	100.0%	85%
D	MM	100.0%	100.0%	85%
H	MM	100.0%	100.0%	85%
K	MM	100.0%	100.0%	85%
P	MM	95.8%	99.7%	85%
U	MM	100.0%	100.0%	85%
Y	MM	100.0%	100.0%	85%
Z	MM	91.7%	94.4%	85%

The average and standard deviation of Crossfall regression 3.2 m for system categories and reference is presented in Figure 32.

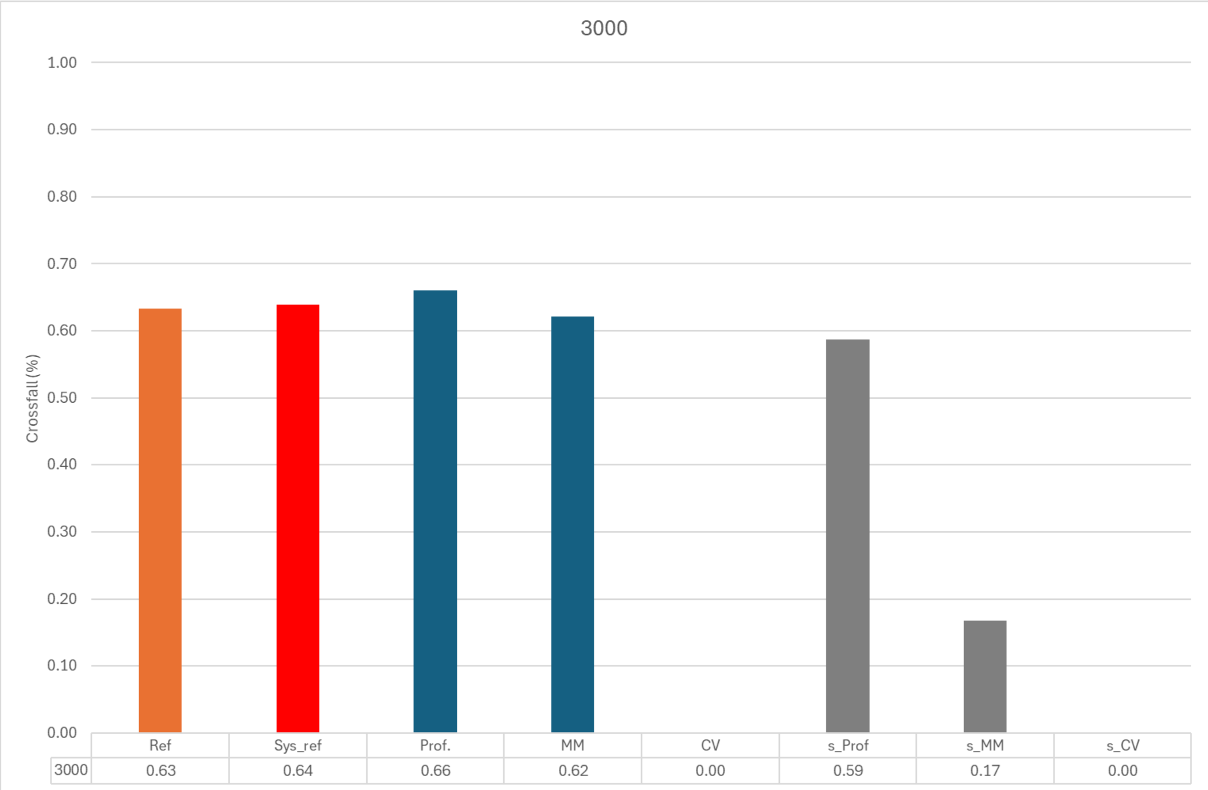


Figure 32 Overall average and standard deviation of Crossfall regression 3.2 m.

A more detailed comparison, at 20 m level, between the references and the average of the repeated runs for the participant categories can be seen in Figure 33. The following figures, Figure 33 through Figure 35, are marked with black vertical lines to indicate the end and start of a test section. For Crossfall, the relevant sections are A, C, and D.

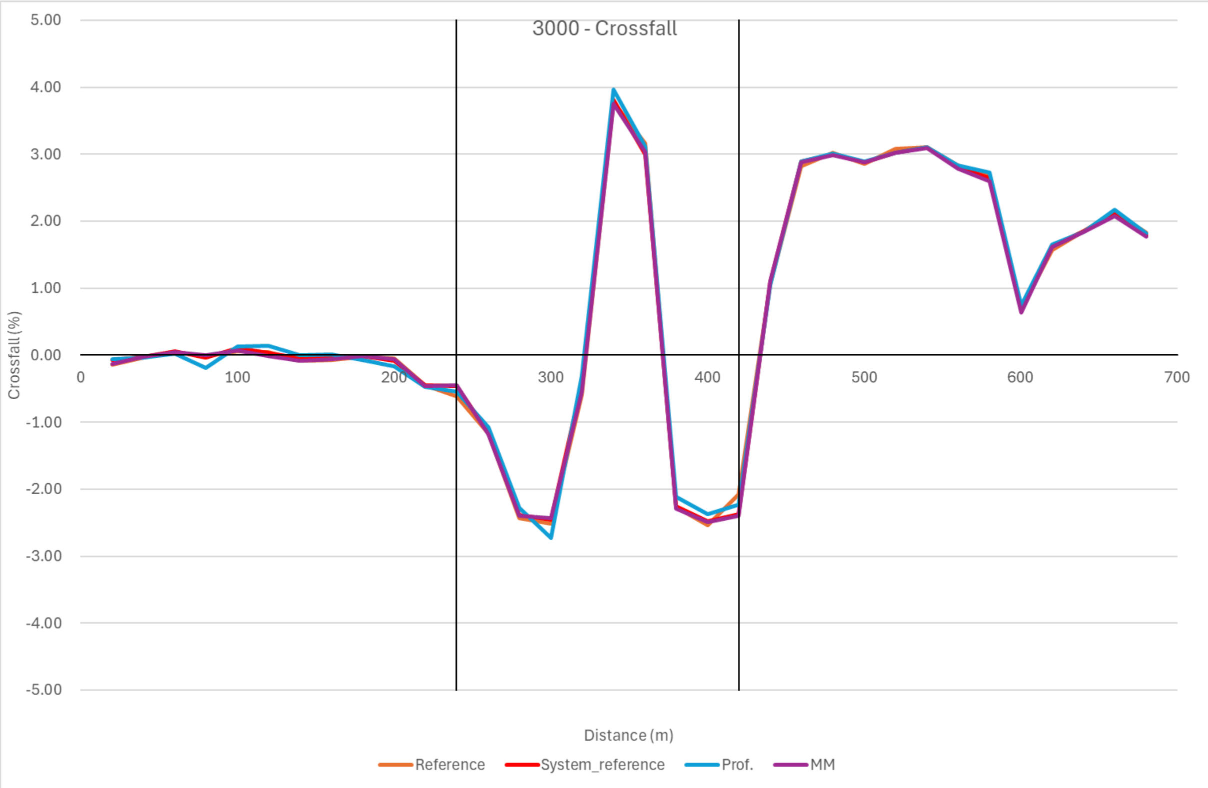


Figure 33 Crossfall regression 3.2 m, 20 m comparison between references and the average of the two participant categories.

The individual participants' average results for the two categories compared with the references can be seen in Figure 34 and Figure 35.

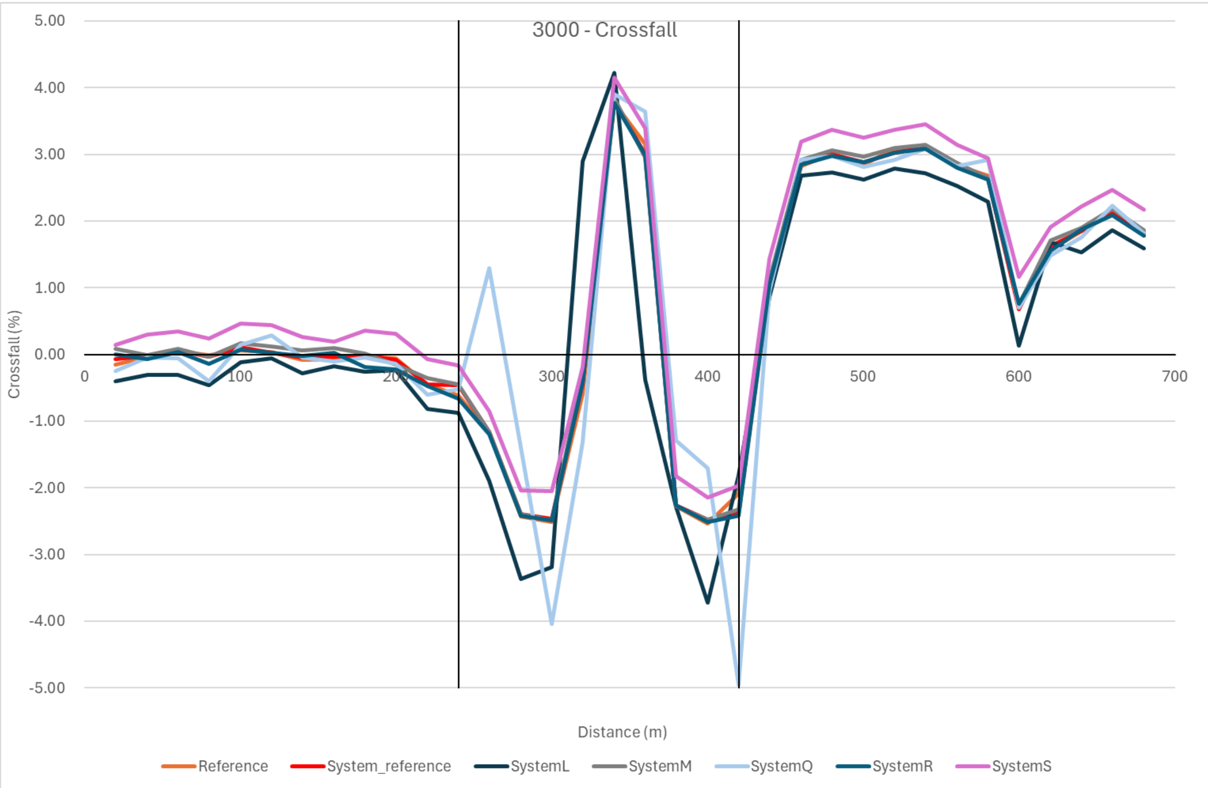


Figure 34 Crossfall regression 3.2 m: a comparison between reference values and the average of the measurements obtained by participants in the profilometer category.

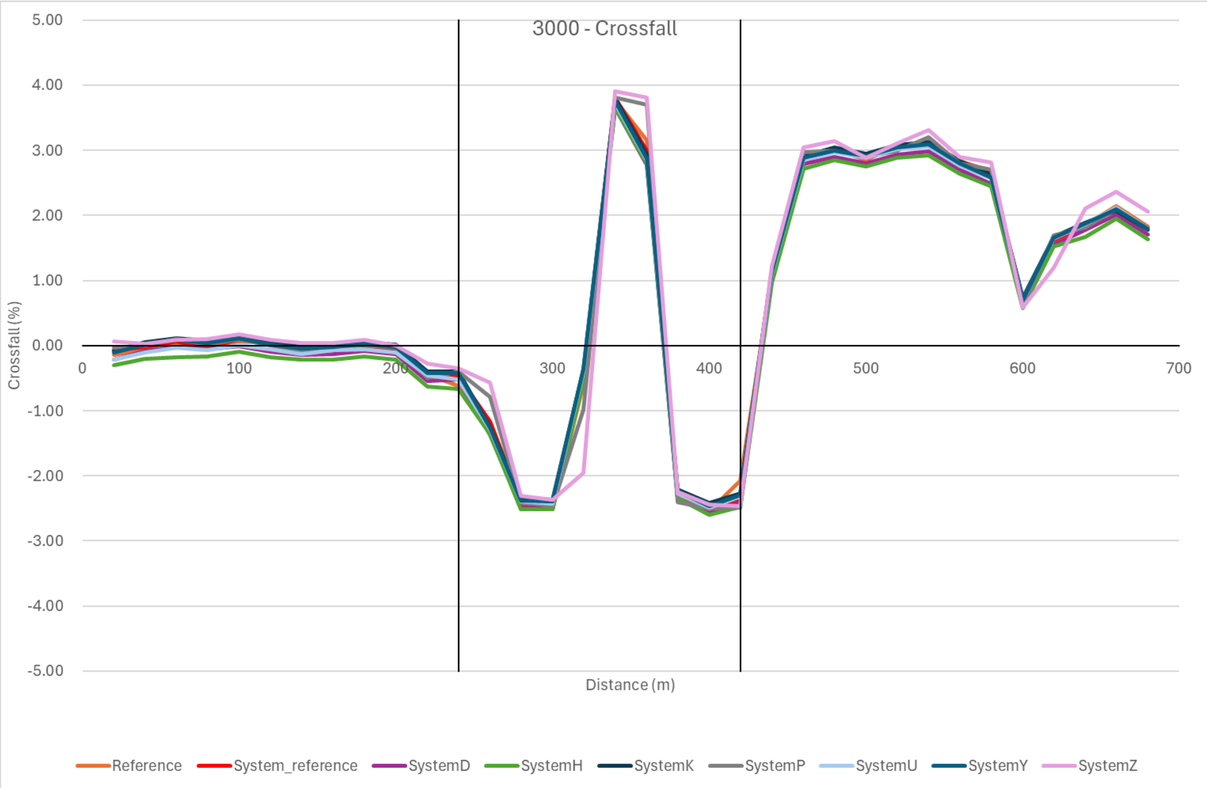


Figure 35 Crossfall regression 3.2 m: a comparison between reference values and the average of the measurements obtained by participants in the mobile mapping category.

9.1.5. TermID 1547 – Hilliness

Hilliness reference is calculated from the reference longitudinal profile in the centre position of the vehicle/test section. The two references utilized are the dedicated reference measurement and the system average. A total of 12 systems provided Hilliness data.

Initially, results from participants are compared to the references. This comparison follows the procedures outlined in chapter 7.1, using threshold levels specified in Annex 1. The comparison is performed for each subsection, at 20 m interval, and each repetition. For example, as shown in Table 14, System L achieved 78.5% within limit1 according to the dedicated reference measurements. The results are divided into two tables, comparison with reference (Table 16) and system reference (Table 17).

Table 16 Validity of participants results for Hilliness compared with reference measurement.

System	Category	Validity_Ref1	Validity_Ref2	Requirement
J	P	82.4%	92.6%	90%
L	P	100.0%	100.0%	90%
M	P	100.0%	100.0%	90%
Q	P	87.5%	94.9%	90%
R	P	100.0%	100.0%	90%
D	MM	100.0%	100.0%	90%
E	MM	100.0%	100.0%	90%
K	MM	100.0%	100.0%	90%

P	MM	95.0%	100.0%	90%
U	MM	100.0%	100.0%	90%
Y	MM	100.0%	100.0%	90%
Z	MM	95.5%	95.9%	90%

Table 17 Validity of participants results for Hilliness compared with system reference measurement.

System	Category	Validity_Sysref1	Validity_Sysref2	Requirement
J	P	83.5%	93.8%	90%
L	P	100.0%	100.0%	90%
M	P	100.0%	100.0%	90%
Q	P	87.5%	94.3%	90%
R	P	100.0%	100.0%	90%
D	MM	100.0%	100.0%	90%
E	MM	100.0%	100.0%	90%
K	MM	100.0%	100.0%	90%
P	MM	95.0%	100.0%	90%
U	MM	100.0%	100.0%	90%
Y	MM	100.0%	100.0%	90%
Z	MM	95.5%	95.9%	90%

The average and standard deviation of Hilliness for system categories and reference is presented in Figure 36.

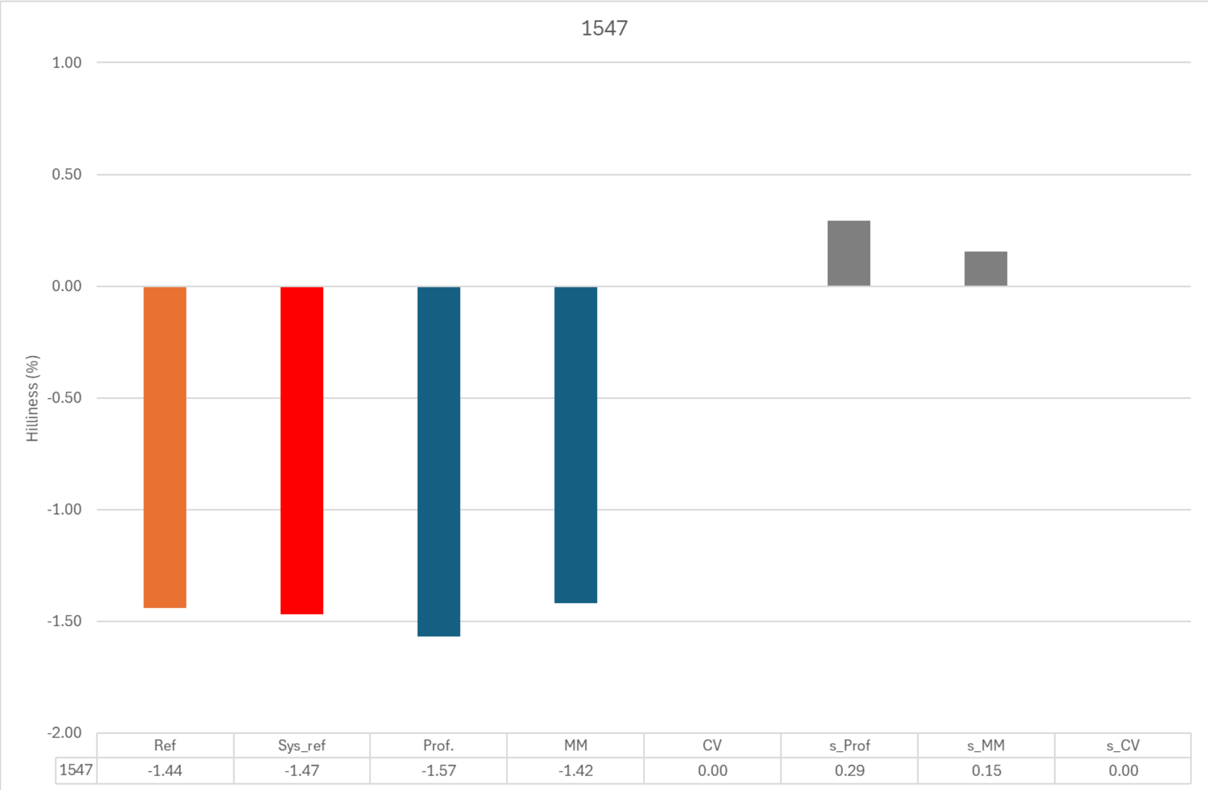


Figure 36 Overall average and standard deviation of Hilliness.

A more detailed comparison, at 20 m level, between the references and the average of the repeated runs for the participant categories can be seen in Figure 37. The following figures, Figure 37 through Figure 39, are marked with black vertical lines to indicate the end and start of a test section. For Hilliness, the relevant sections are A, C, and D.

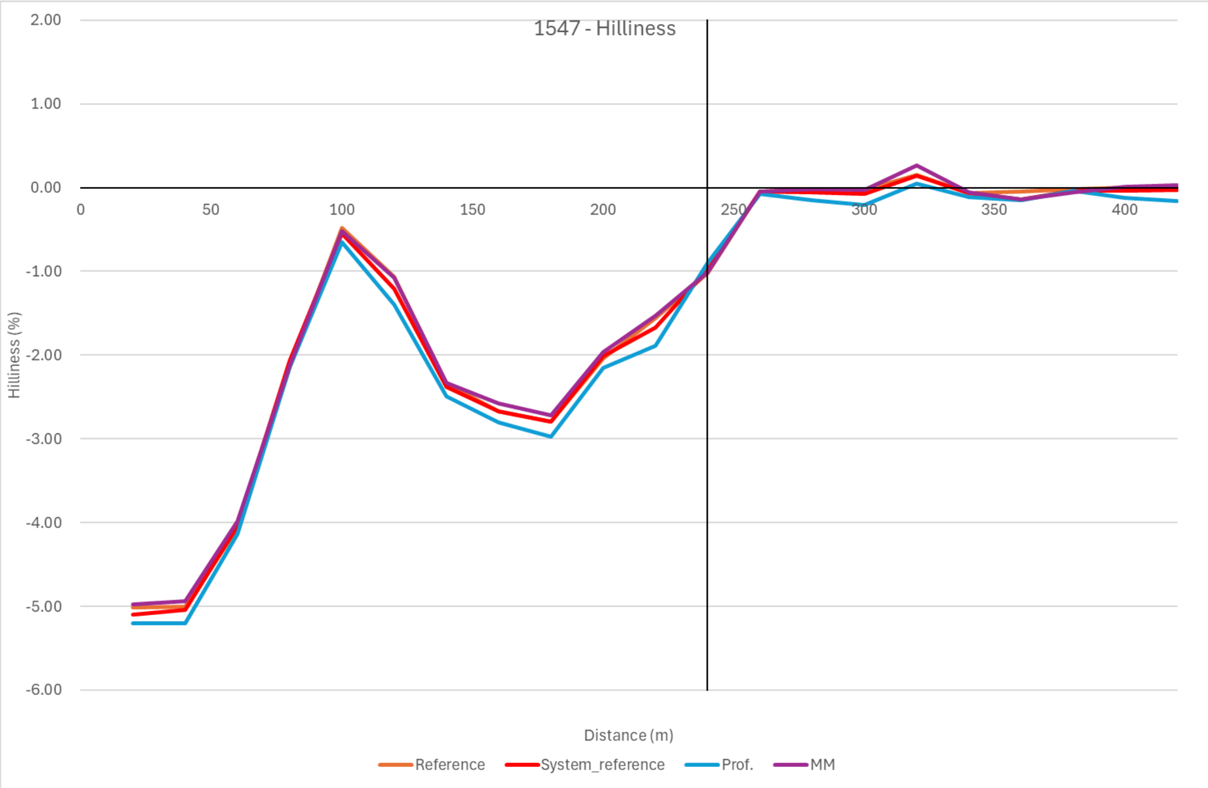


Figure 37 Hilliness, 20 m comparison between references and the average of the two participant categories.

The individual participants average results for the two categories compared with the references can be seen in Figure 38 and Figure 39.

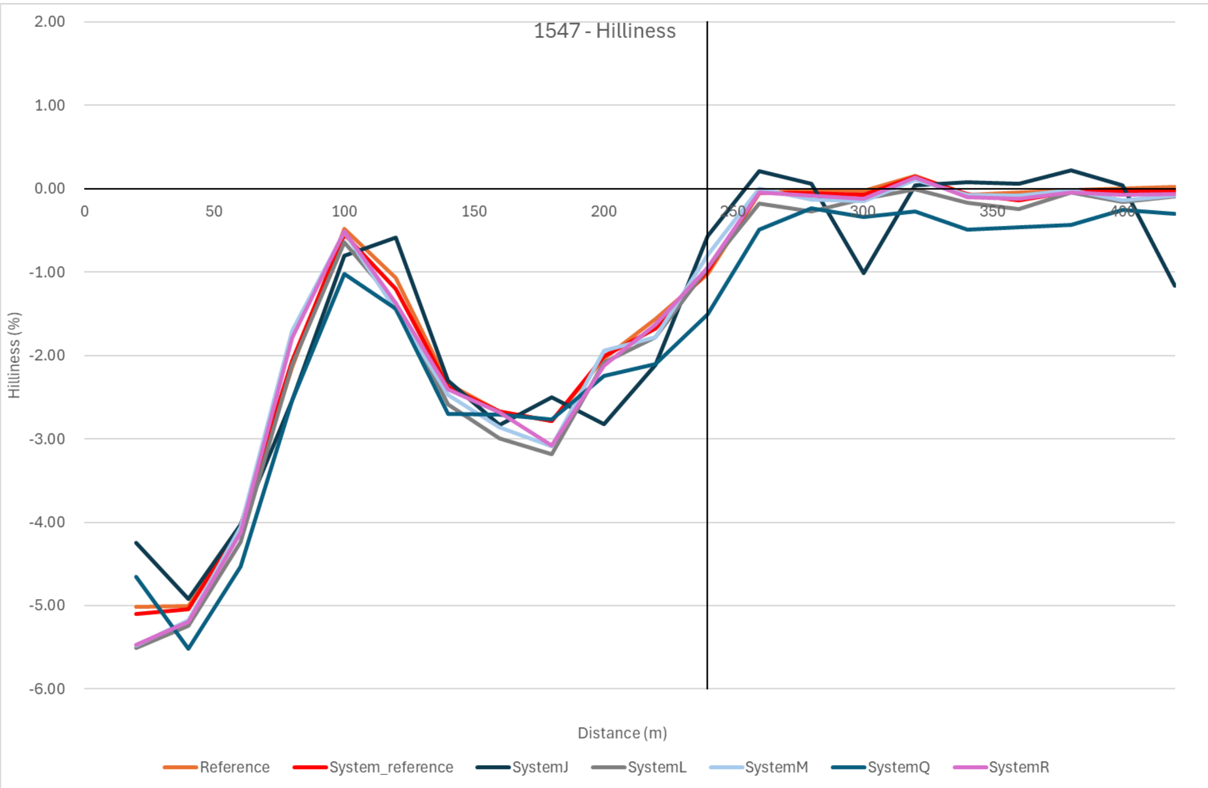


Figure 38 Hilliness: a comparison between reference values and the average of the measurements obtained by participants in the profilometer category.

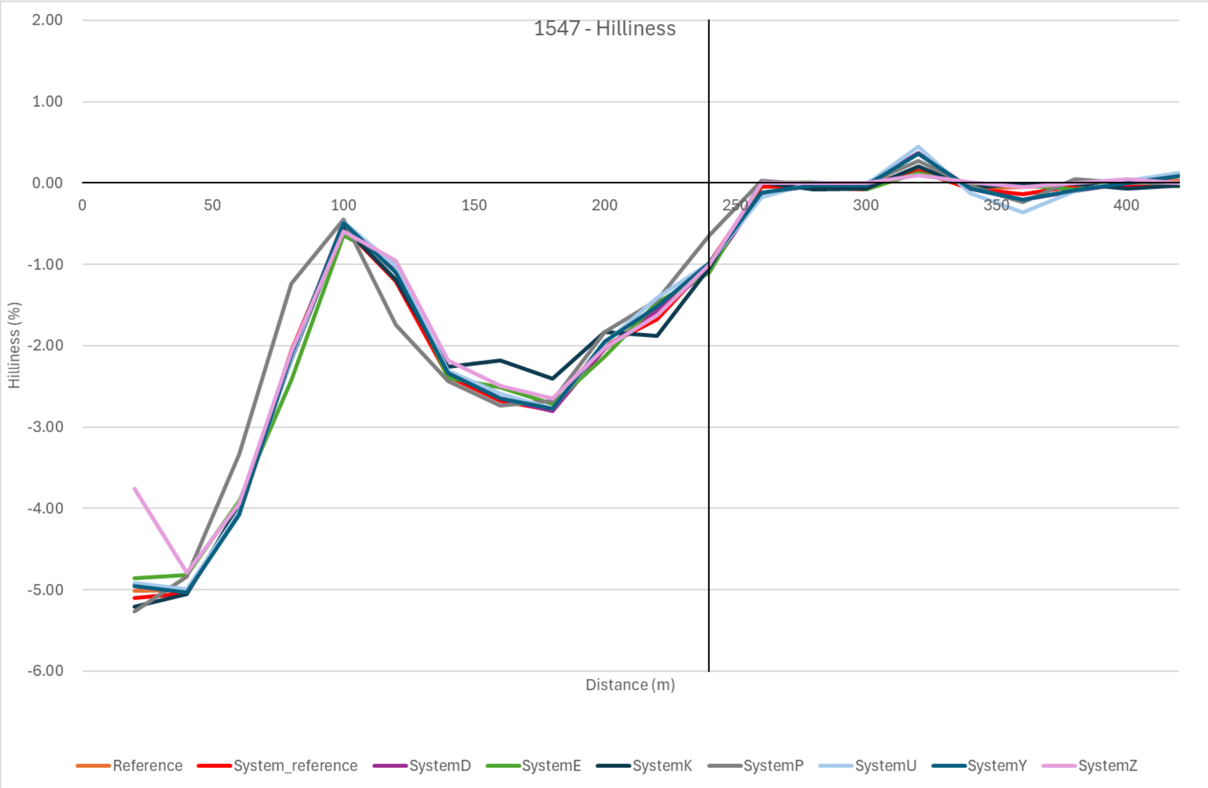


Figure 39 Hilliness: a comparison between reference values and the average of the measurements obtained by participants in the mobile mapping category

9.1.6. TermID 3302 – MPD right wheel track

The reference MPD is calculated from the reference texture profile in the right wheel track. The two references utilized are a dedicated reference measurement and the system average. A total of 12 systems provided MPD data.

Initially, results from participants are compared to the references. This comparison follows the procedures outlined in chapter 7.1, using threshold levels specified in Annex 1. The comparison is performed for each subsection, at 20 m interval, and each repetition. For example, as shown in Table 18 System I achieved 53.2% within limit1 according to the dedicated reference measurements. The results are divided into two tables, comparison with reference (Table 18) and system reference (Table 19).

Table 18 Validity of participants results for MPD in right wheel track compared with reference measurement.

System	Category	Validity_Ref1	Validity_Ref2	Requirement
I	P	53.2%	80.8%	70%
J	P	73.2%	98.2%	70%
L	P	0.5%	5.1%	70%
M	P	91.9%	100.0%	70%
O	P	19.4%	44.4%	70%
Q	P	7.9%	10.7%	70%
R	P	82.2%	100.0%	70%
S	P	68.5%	95.8%	70%

System	Category	Validity_Ref1	Validity_Ref2	Requirement
T	P	53.2%	81.2%	70%
E	MM	49.4%	85.8%	70%
H	MM	36.1%	86.5%	70%
P	MM	15.3%	50.0%	70%

Table 19 Validity of participants results for MPD in right wheel track compared with system reference.

System	Category	Validity_Sysref1	Validity_Sysref2	Requirement
I	P	88.0%	88.0%	70%
J	P	95.8%	98.2%	70%
L	P	3.7%	17.6%	70%
M	P	79.6%	100.0%	70%
O	P	46.8%	65.3%	70%
Q	P	5.6%	23.6%	70%
R	P	92.6%	96.3%	70%
S	P	95.4%	96.3%	70%
T	P	88.0%	88.0%	70%
E	MM	17.3%	56.8%	70%
H	MM	74.0%	90.9%	70%
P	MM	5.1%	33.3%	70%

The average and standard deviation of MPD in right wheel track for system categories and reference is presented in Figure 40.

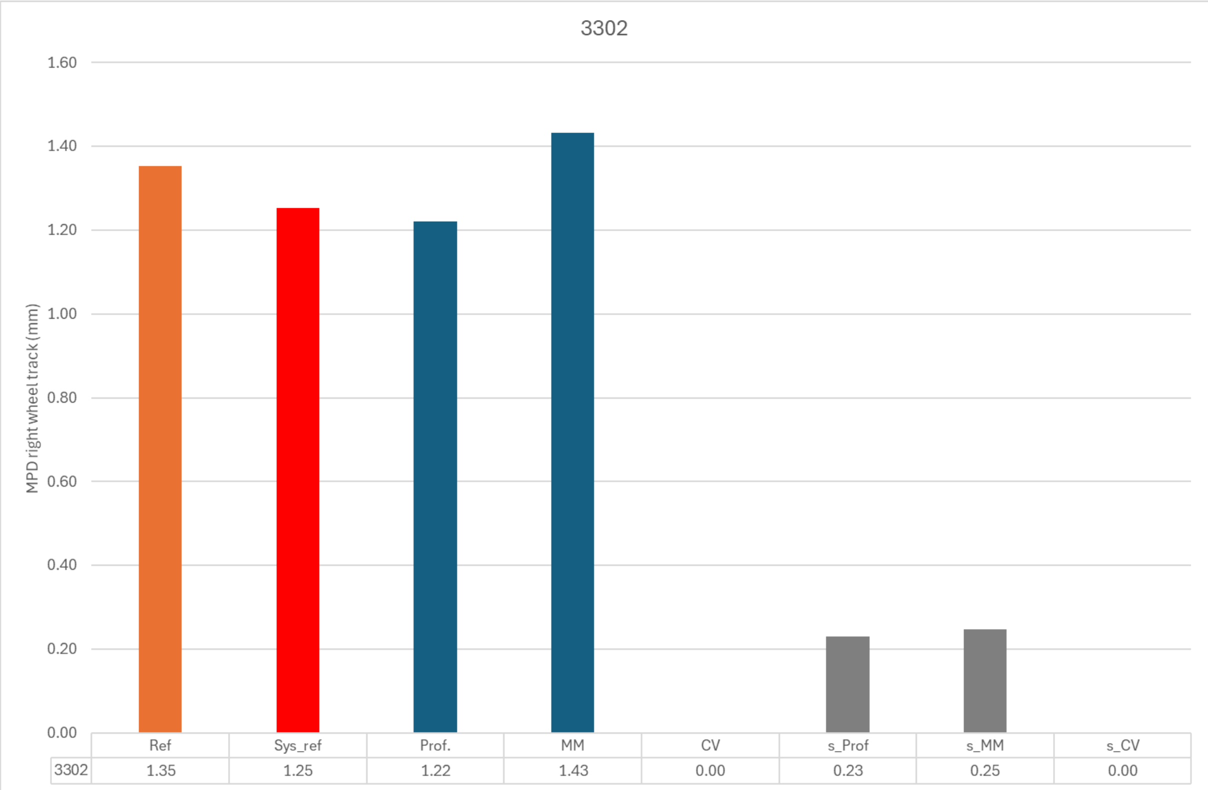


Figure 40 Overall average and standard deviation of MPD in right wheel track.

A more detailed comparison, at 20 m level, between the references and the average of the repeated runs for the participant categories can be seen in Figure 41. The following figures, Figure 41 through Figure 43, are marked with a black vertical line to indicate the end and start of a test section. For MPD, the relevant sections are A and D.

Figure 41 MPD, 20 m comparison between references and the average of the two participant categories.

The individual participants' average results for the two categories compared with the references can be seen in Figure 42 and Figure 43.

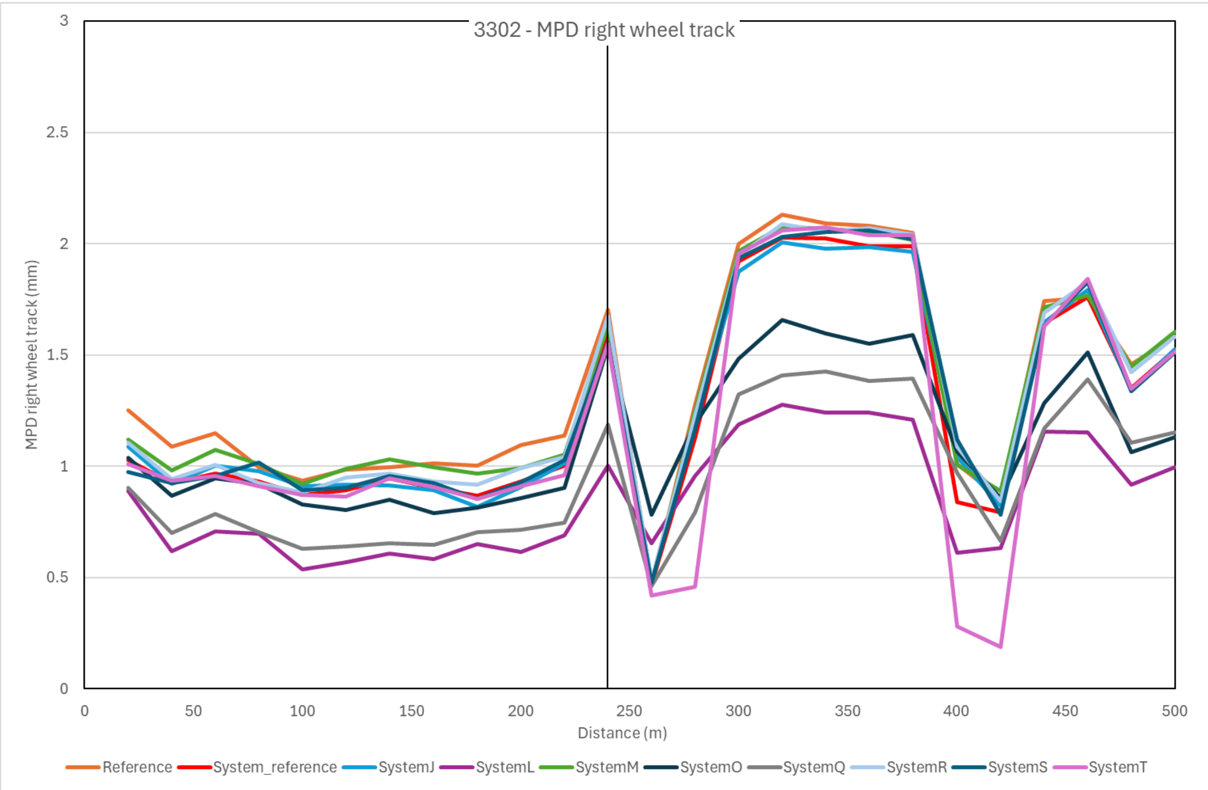


Figure 42 MPD: comparison of reference values with each participant's average in the profilometer category.

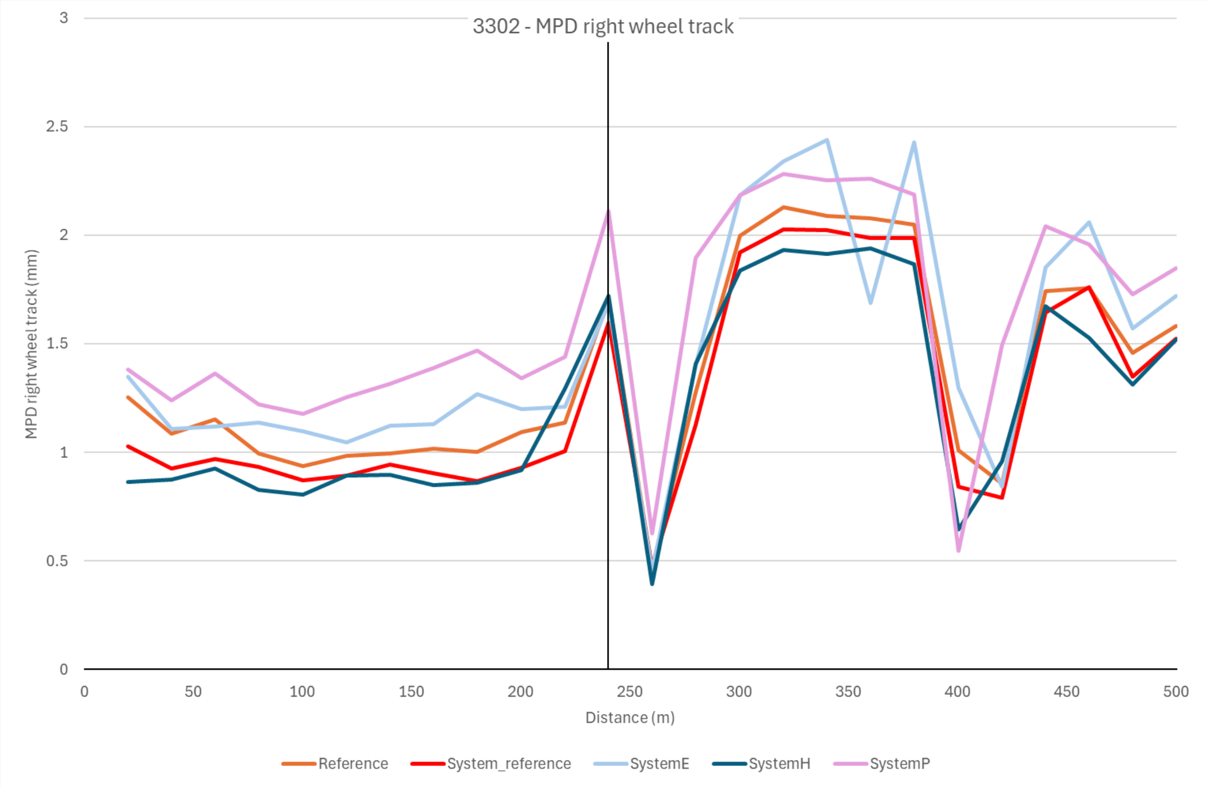


Figure 43 MPD: comparison of reference values with each participant's average in the mapping category.

9.1.7. TermID 3109 – Megatexture right wheel track

The reference Megatexture is calculated from the reference texture profile in the right wheel track. The two references utilized are a dedicated reference measurement and the system average. A total of 3 systems provided Megatexture data.

Initially, results from participants are compared to the references. This comparison follows the procedures outlined in chapter 7.1, using threshold levels specified in Annex 1. The comparison is performed for each subsection, at 20 m interval, and each repetition. For example, as shown in Table 20, System J achieved 74.5% within limit1 according to the dedicated reference measurements. The results are divided into two tables, comparison with reference (Table 20) and system reference (Table 21).

Table 20 Validity of participants results for Megatexture in right wheel track compared with reference measurement.

System	Category	Validity_Ref1	Validity_Ref2	Requirement
J	P	74.5%	99.5%	85%
M	P	98.9%	99.3%	85%
R	P	97.8%	100.0%	85%

Table 21 Validity of participants results for Megatexture in right wheel track compared with system reference.

System	Category	Validity_Sysref1	Validity_Sysref2	Requirement
J	P	100.0%	100.0%	85%

System	Category	Validity_Sysref1	Validity_Sysref2	Requirement
M	P	98.9%	99.3%	85%
R	P	100.0%	100.0%	85%

The average and standard deviation of Megatexture in right wheel track for system categories and reference is presented in Figure 40.

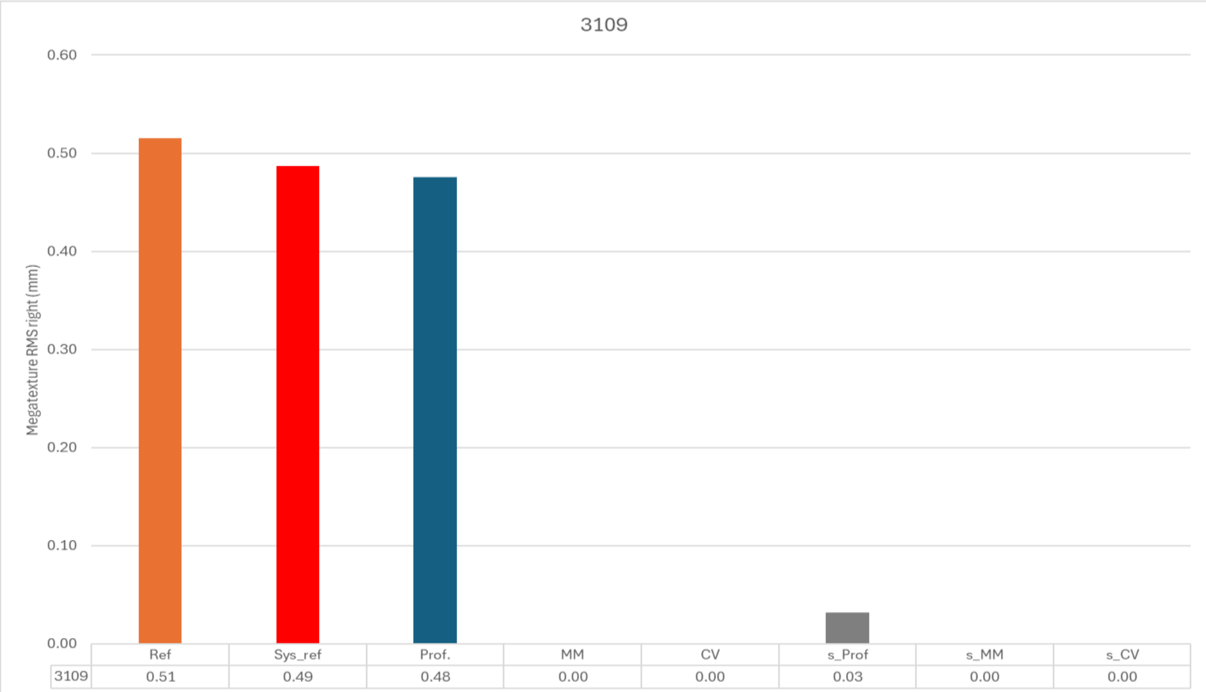


Figure 44 Overall average and standard deviation of Megatexture in right wheel track.

A more detailed comparison, at 20 m level, between the references and the average of the repeated runs for the participant categories can be seen in Figure 45. The following figures, Figure 45 and Figure 46, are marked with a black vertical line to indicate the end and start of a test section. For Megatexture, the relevant sections are A and D.

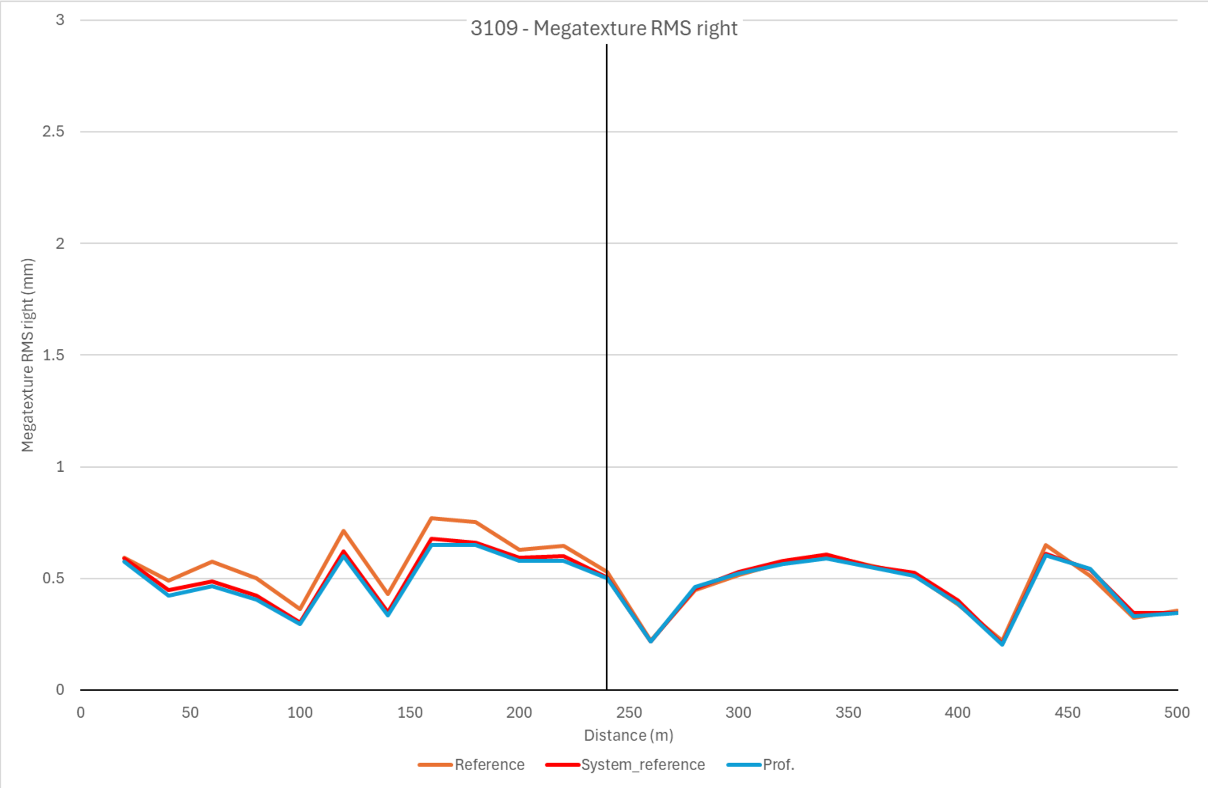


Figure 45 Megatexture, 20 m comparison between references and the average of the participant category.

The individual participants' average results for the profilometer categories compared with the references can be seen in Figure 46.

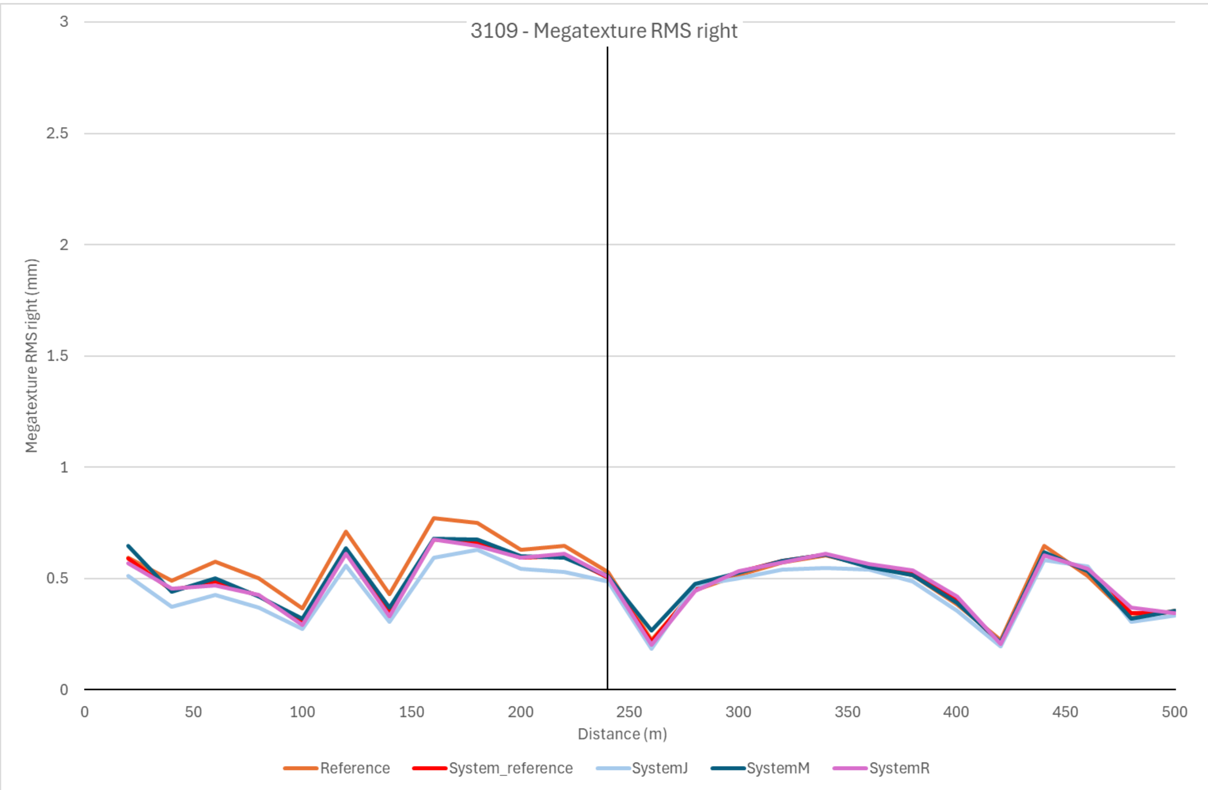


Figure 46 Megatexture: comparison of reference values with each participant's average in the profilometer category.

9.1.8. TermID 3800 – WLPσ right wheel track

The reference WLPσ is calculated from the reference longitudinal profile in the right wheel track. The two references utilized are a dedicated reference measurement and the system average. A total of 3 systems provided WLP data.

Initially, results from participants are compared to the references. This comparison follows the procedures outlined in chapter 7.1, using threshold levels specified in Annex 1. The comparison is performed for each subsection, at 20 m interval, and each repetition. For example, as shown in Table 22, System M achieved 54.7% within limit1 according to the dedicated reference measurements. The results are divided into two tables, comparison with reference (Table 22) and system reference (Table 23). There is no requirement used in Sweden or Finland for this variable.

Table 22 Validity of participants results for WLPσ in right wheel track compared with reference measurement.

System	Category	Validity_Ref1	Validity_Ref2	Requirement
M	P	54.7%	63.3%	
E	MM	65.2%	79.7%	
Z	MM	58.9%	74.7%	

Table 23 Validity of participants results for WLPσ in right wheel track compared with system reference.

System	Category	Validity_Sysref1	Validity_Sysref2	Requirement
M	P	79.4%	84.2%	
E	MM	41.1%	73.0%	
Z	MM	51.9%	69.7%	

The average and standard deviation of WLPσ in right wheel track for system categories and reference is presented in Figure 47.

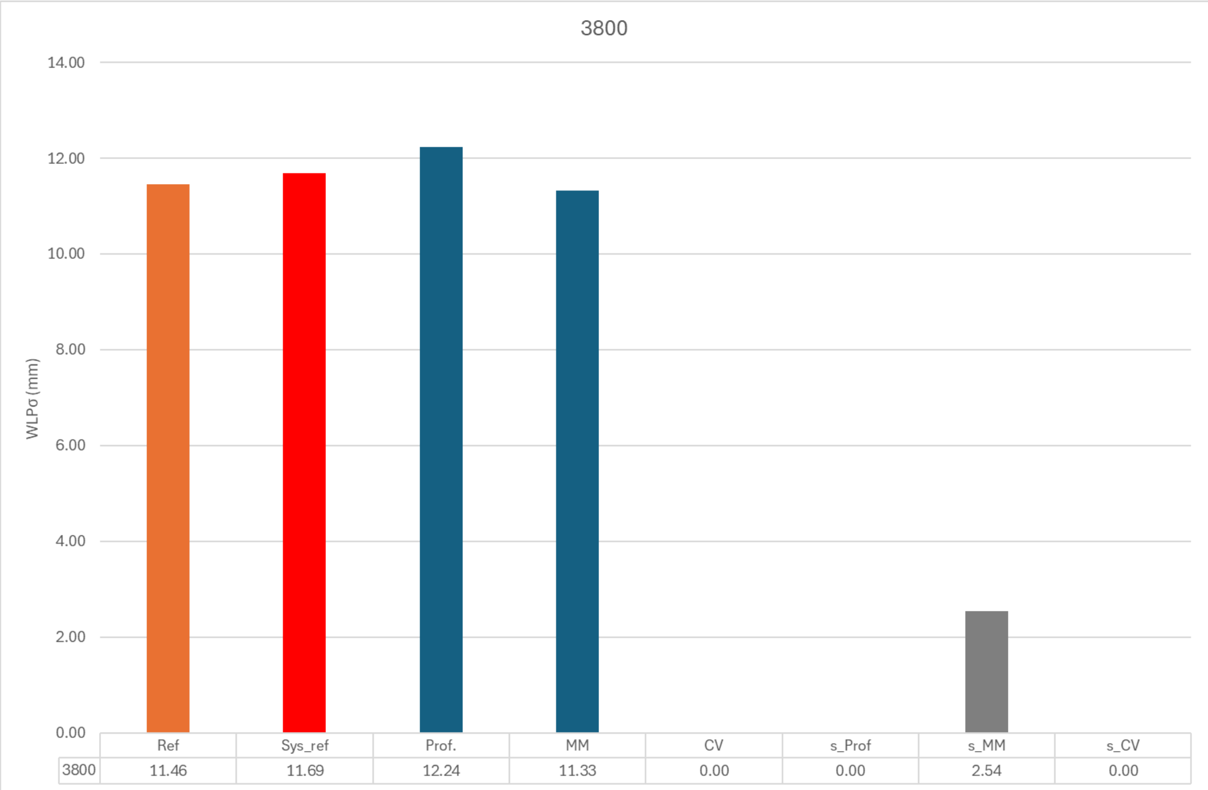


Figure 47 Overall average and standard deviation of WLPσ in right wheel track.

A more detailed comparison, at 20 m level, between the references and the average of the repeated runs for the participant categories can be seen in Figure 48. The following figures, Figure 48 through Figure 50, are marked with black vertical lines to indicate the end and start of a test section. For WLPσ, the relevant sections are A, C, and D.

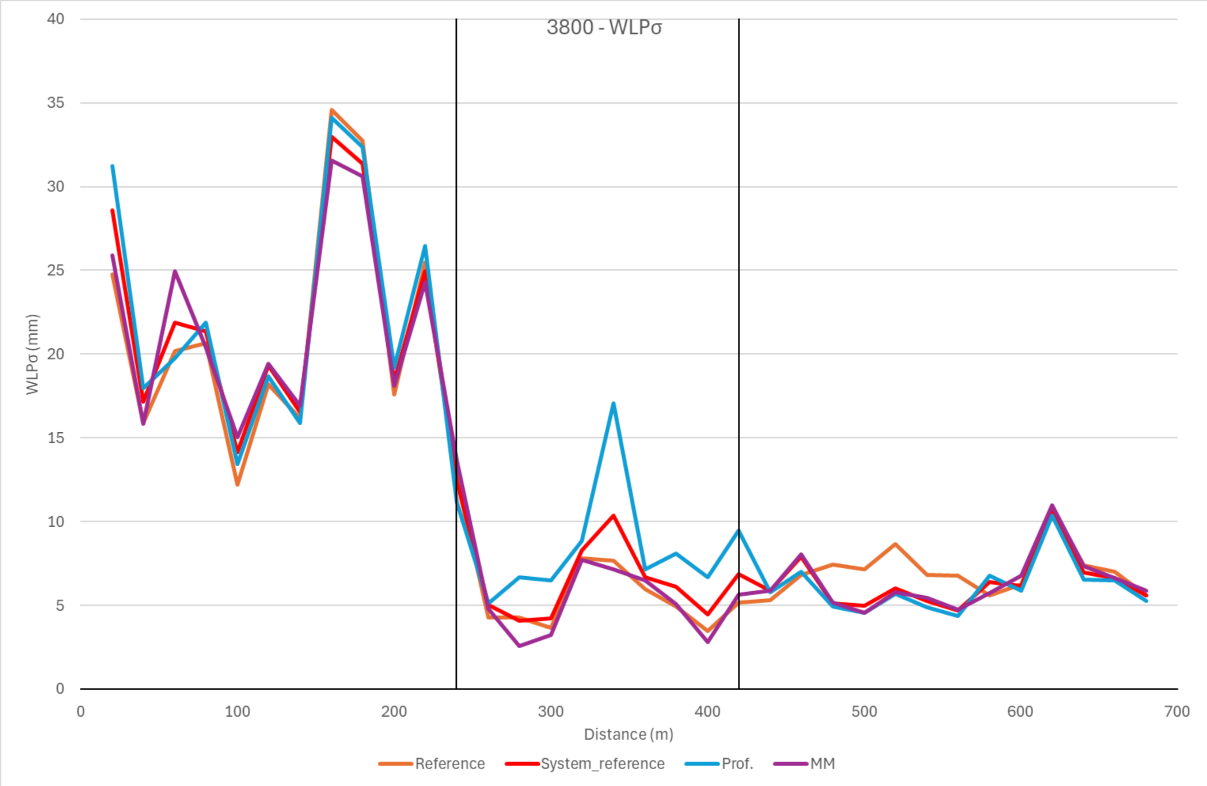


Figure 48 WLPσ, 20 m comparison between references and the average of the two participant categories.

The individual participants' average results for the two categories compared with the references can be seen in Figure 49 and Figure 50.

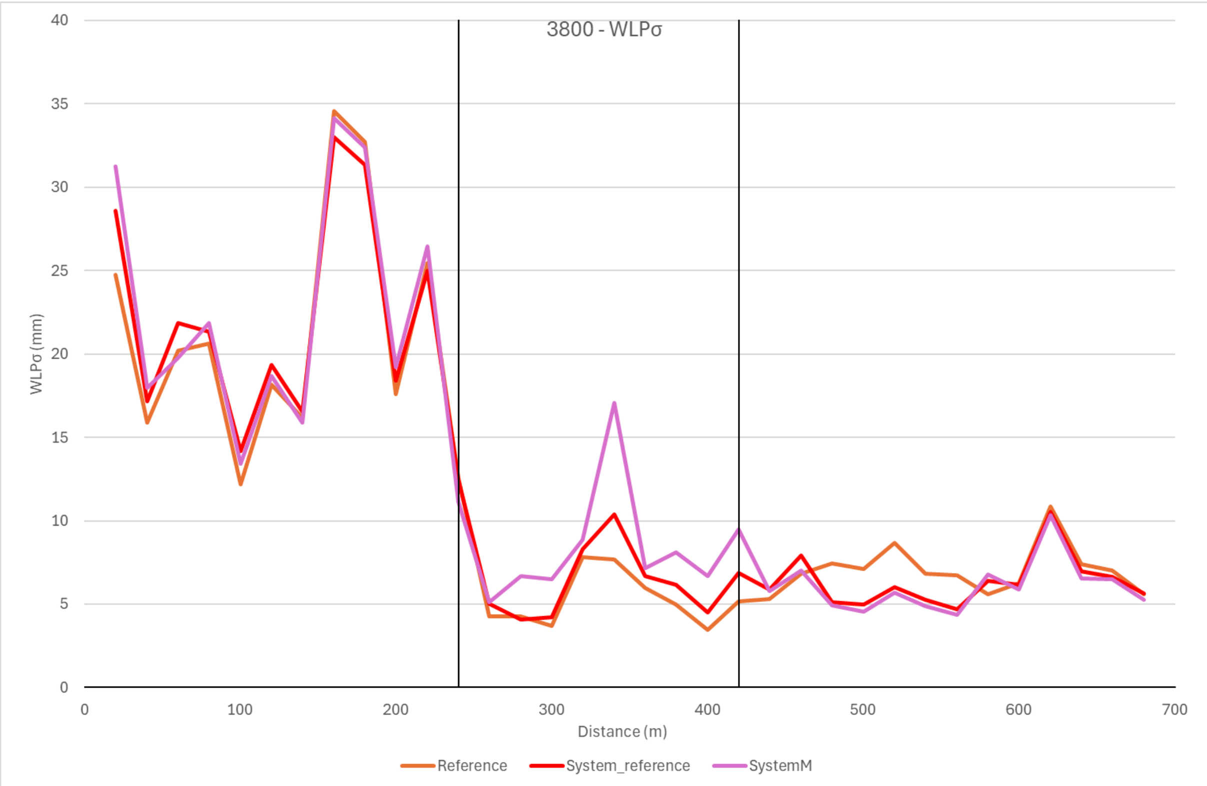


Figure 49 WLPσ: comparison of reference values with each participant's average in the profilometer category.

Figure 50 WLPσ: comparison of reference values with each participant's average in the mobile mapping category.

9.1.9. TermID 3801 – WLPΔ right wheel track

The reference WLPΔ is calculated from the reference longitudinal profile in the right wheel track. The two references utilized are a dedicated reference measurement and the system average. A total of 3 systems provided WLP data.

Initially, results from participants are compared to the references. This comparison follows the procedures outlined in chapter 7.1, using threshold levels specified in Annex 1. The comparison is performed for each subsection, at 20 m interval, and each repetition. For example, as shown in Table 24 System M achieved 46.1% within limit1 according to the dedicated reference measurements. The results are divided into two tables, comparison with reference (Table 24) and system reference (Table 25). There is no requirement used in Sweden or Finland for this variable.

Table 24 Validity of participants results for WLPΔ in right wheel track compared with reference measurement.

System	Category	Validity_Ref1	Validity_Ref2	Requirement
M	P	46.1%	66.1%	
E	MM	45.4%	67.6%	
Z	MM	51.9%	72.5%	

Table 25 Validity of participants results for WLPΔ in right wheel track compared with system reference.

System	Category	Validity_Sysref1	Validity_Sysref2	Requirement
M	P	71.9	88.1	0%
E	MM	41.1	65.7	0%

System	Category	Validity_Sysref1	Validity_Sysref2	Requirement
Z	MM	53.6	69.7	0%

The average and standard deviation of WLPΔ in right wheel track for system categories and reference is presented in Figure 51.

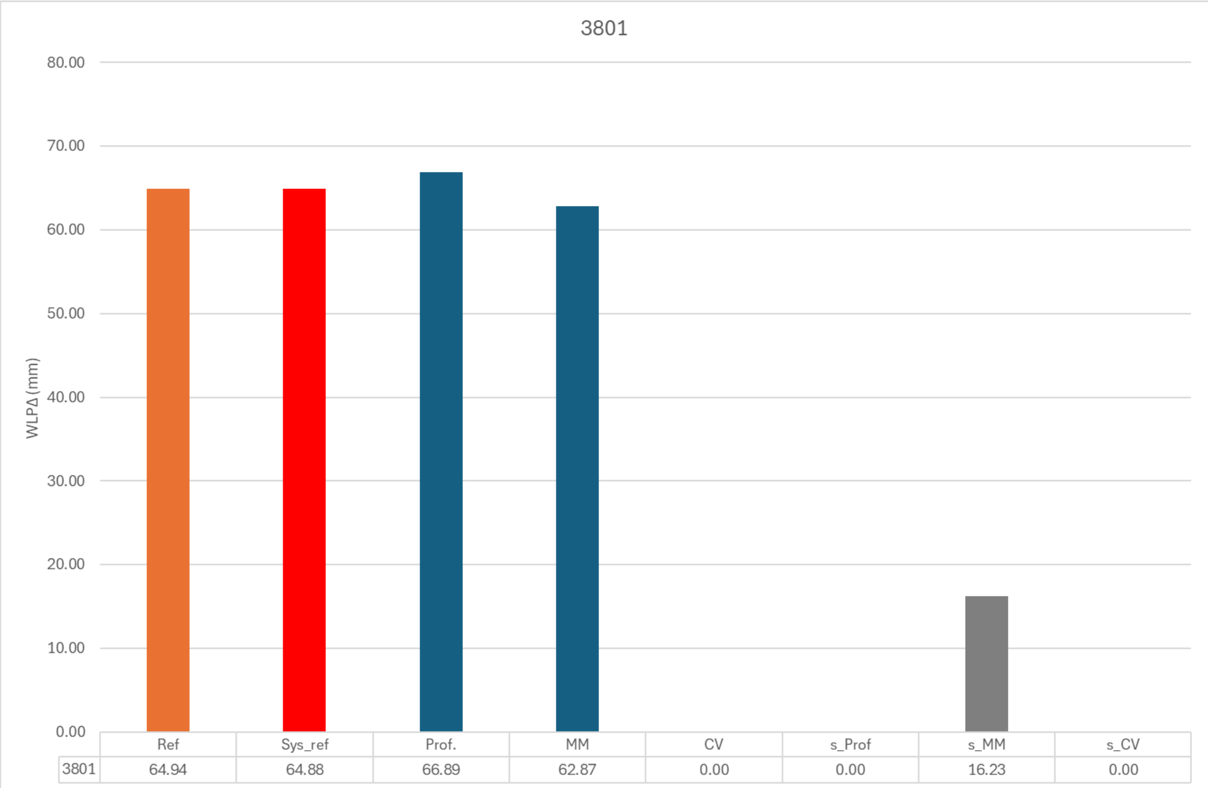


Figure 51 Overall average and standard deviation of WLPΔ in right wheel track.

A more detailed comparison, at 20 m level, between the references and the average of the repeated runs for the participant categories can be seen in Figure 52. The following figures, Figure 52 through Figure 54, are marked with black vertical lines to indicate the end and start of a test section. For WLPΔ, the relevant sections are A, C, and D.

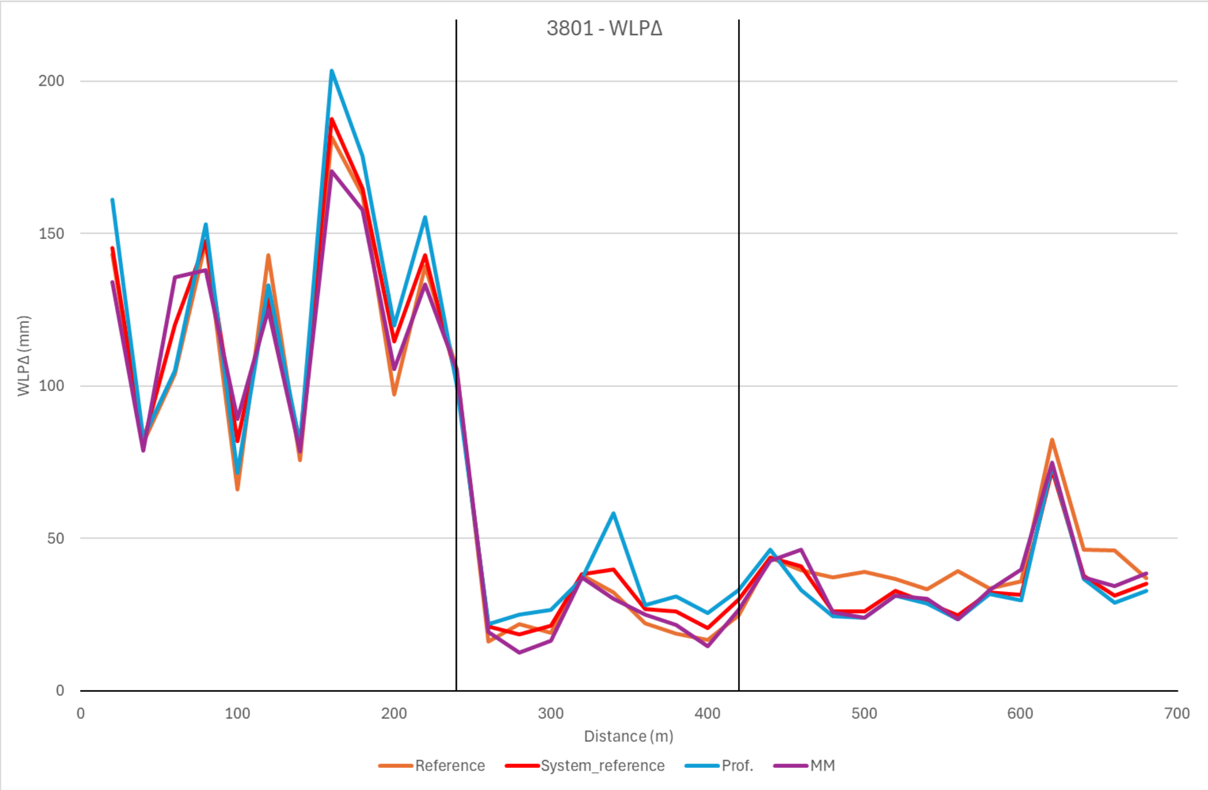


Figure 52 WLPΔ, 20 m comparison between references and the average of the two participant categories.

The individual participants' average results for the two categories compared with the references can be seen in Figure 53 and Figure 54.

Figure 53 WLPΔ: comparison of reference values with each participant's average in the profilometer category.

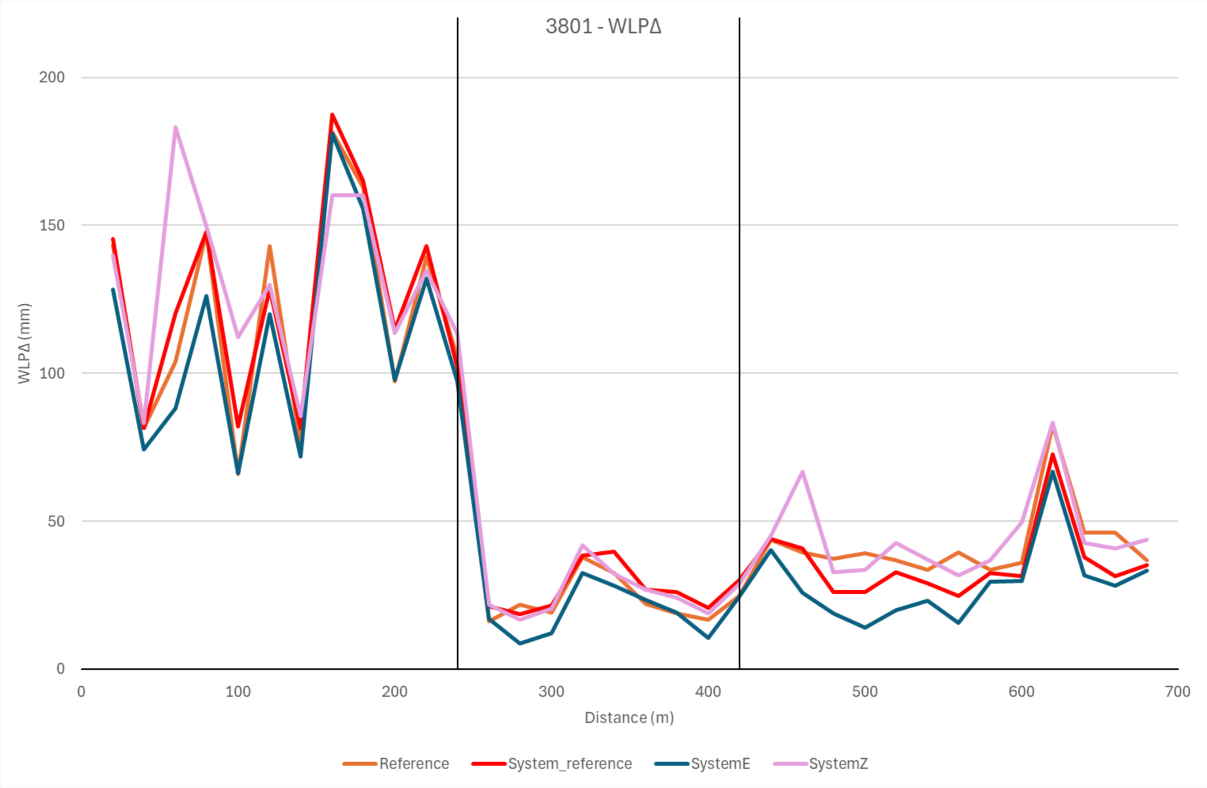


Figure 54 WLPΔ: comparison of reference values with each participant's average in the mobile mapping category.

9.1.10. TermID 4100 and 4101 – Position

The reference Position is calculated from the total station in combination with stationary satellite receiver. The two references utilized are the dedicated reference measurement and the system average. A total of 17 systems provided positioning data. The results presented from the positioning data are the distances between the reference and the participants coordinates. In the figures this is presented as termID 14100.

Initially, results from participants are compared to the references. This comparison follows the procedures outlined in chapter 7.1, using threshold levels specified in Annex 1. The comparison is performed for the first 100 m of each subsection, at 20 m interval, and each repetition. For example, as shown in Table 26 System B achieved 5% within limit1 according to the dedicated reference measurements. The results are presented in Table 26.

Table 26 Validity of participants results for Position compared with reference measurement.

System	Category	Validity_Ref1	Validity_Ref2	Requirement
B	P	5.0%	100.0%	98%
L	P	0.0%	55.0%	98%
M	P	0.0%	100.0%	98%
Q	P	12.5%	100.0%	98%
R	P	100.0%	100.0%	98%
S	P	0.0%	37.5%	98%
D	MM	100.0%	100.0%	98%
E	MM	0.0%	100.0%	98%
H	MM	93.8%	93.8%	98%
K	MM	0.0%	100.0%	98%
P	MM	26.3%	100.0%	98%
U	MM	100.0%	100.0%	98%
Y	MM	100.0%	100.0%	98%
Z	MM	99.0%	99.0%	98%
A	CV	0.0%	100.0%	98%
N	CV	0.0%	100.0%	98%
X	CV	11.1%	85.0%	98%

This variable is not compared with the system reference, as it provides no additional information.

The average and standard deviation of Position for system categories and reference is presented in Figure 55.

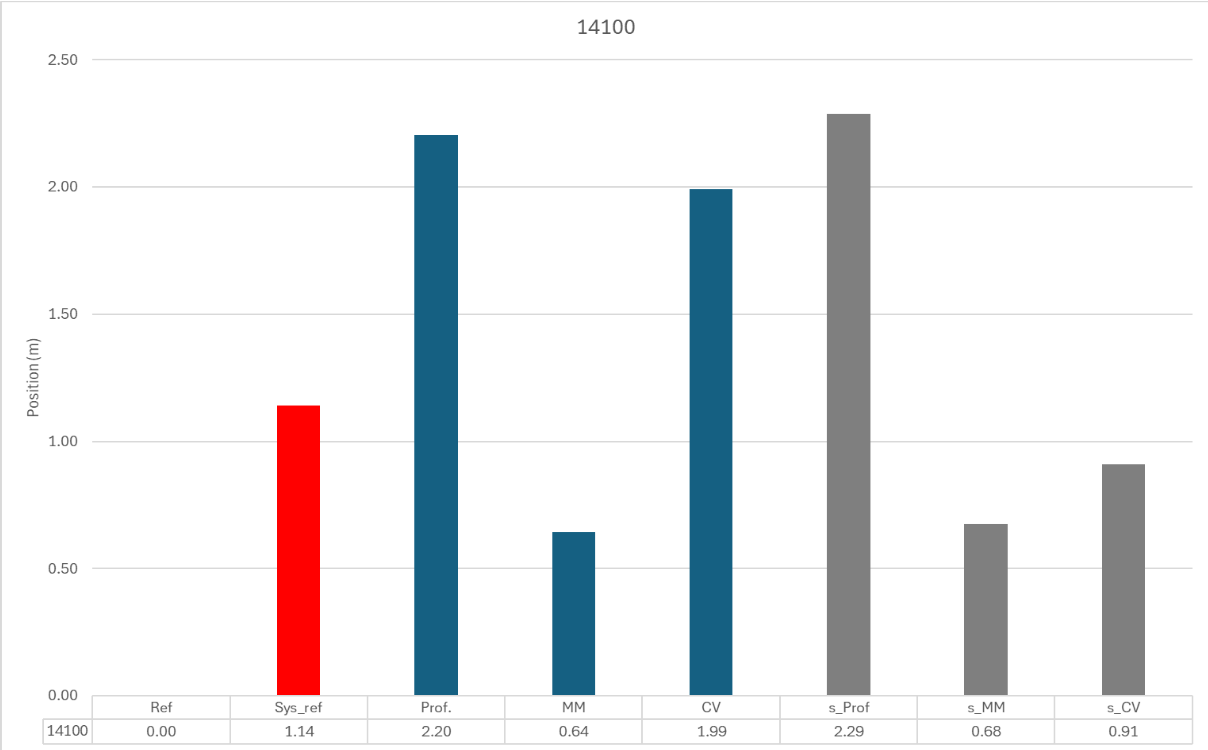


Figure 55 Overall average and standard deviation of Position.

A more detailed comparison, at 20 m level, between the reference and the average of the repeated runs for the participant categories can be seen in Figure 56. The following figures, Figure 56 through Figure 59, are marked with a black vertical line to indicate the end and start of a test section. For Position, the relevant sections are A and D.

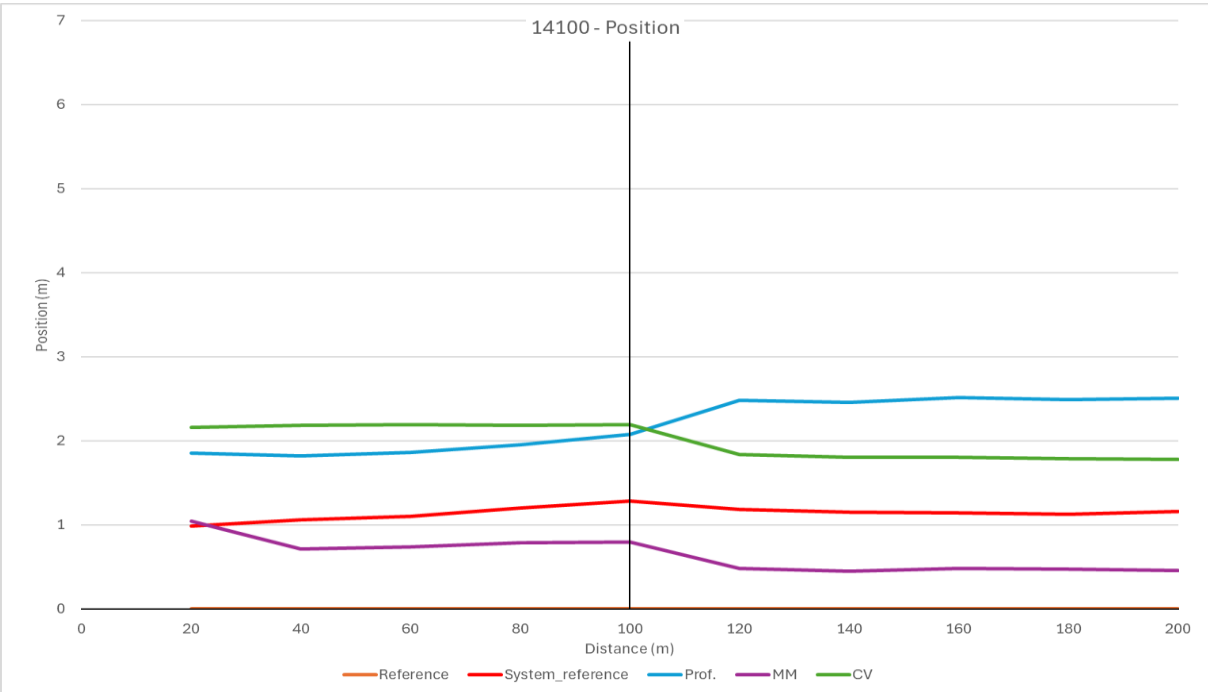


Figure 56 Position, 20 m comparison between references and the average of the three participant categories.

The individual participants average results for the three categories compared with the reference can be seen in Figure 57 to Figure 59.

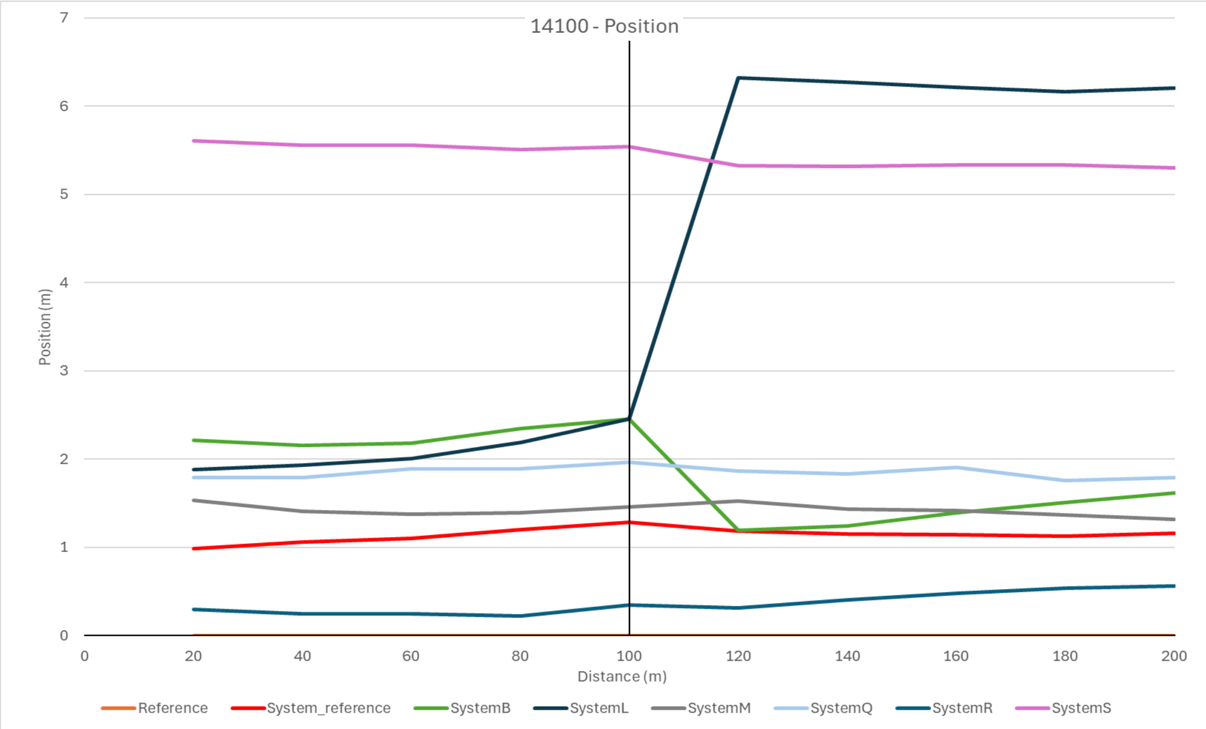


Figure 57 Position: comparison of reference values with each participant's average in the profilometer category.

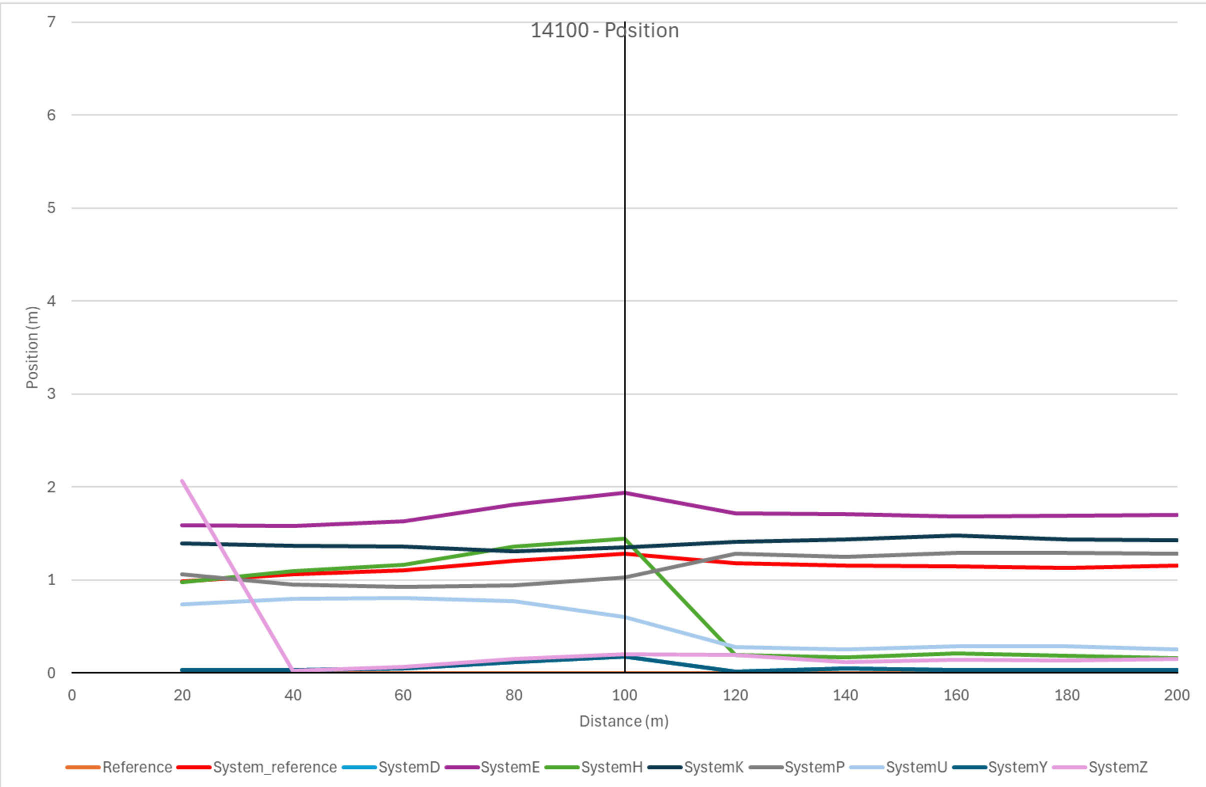


Figure 58 Position: comparison of reference values with each participant's average in the mobile mapping category.

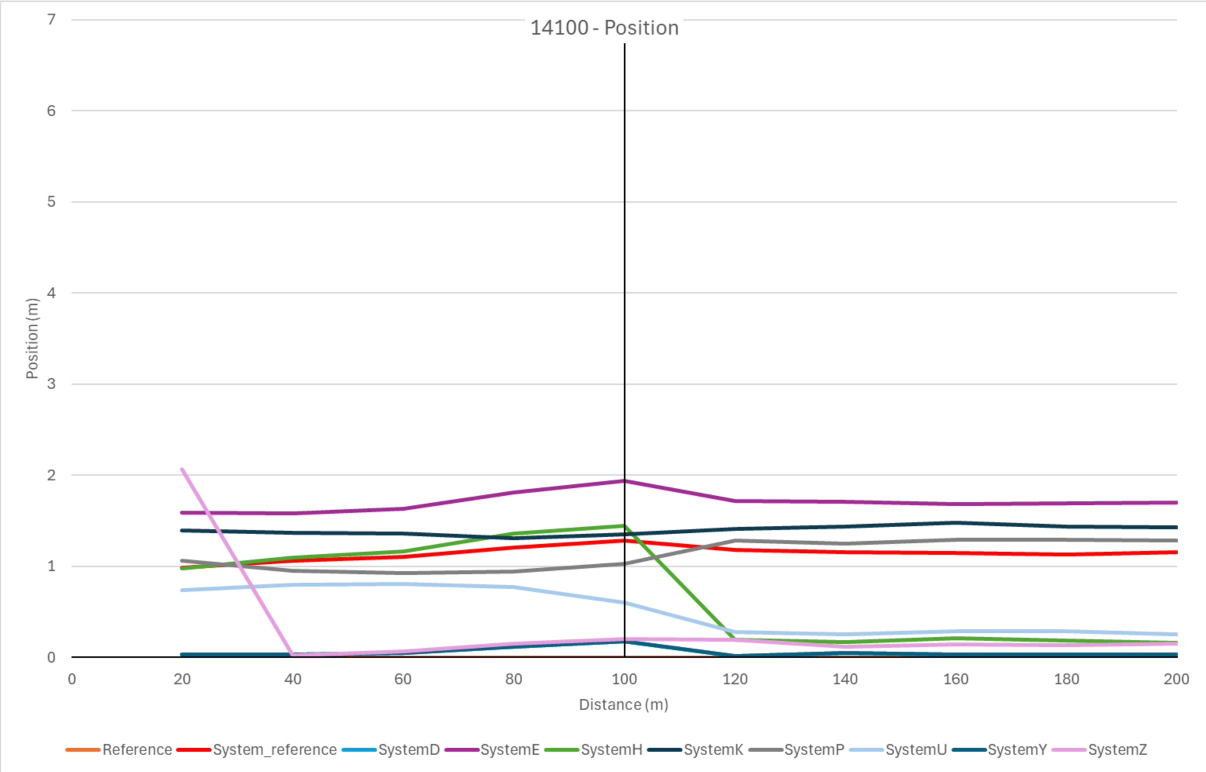


Figure 59 Position: comparison of reference values with each participant's average in the connected vehicle category.

9.1.11. TermID 4102 – Height

The reference Height is calculated from the total station in combination with stationary satellite receiver. The two references utilized are the dedicated reference measurement and the system average. A total of 13 systems provided height data.

Initially, results from participants are compared to the references. This comparison follows the procedures outlined in chapter 7.1, using threshold levels specified in Annex 1. The comparison is performed for the first 100 m of each subsection, at 20 m interval, and each repetition. For example, as shown in Table 27 System L achieved 68.8% within limit1 according to the dedicated reference measurements. The results are presented in Table 27.

Table 27 Validity of participants results for Height compared with reference measurement.

System	Category	Validity_Ref1	Validity_Ref2	Requirement
B	P	0.0%	100.0%	0%
L	P	68.8%	100.0%	0%
M	P	100.0%	100.0%	0%
R	P	36.0%	100.0%	0%
S	P	96.3%	100.0%	0%
D	MM	100.0%	100.0%	0%
E	MM	100.0%	100.0%	0%
H	MM	100.0%	100.0%	0%

System	Category	Validity_Ref1	Validity_Ref2	Requirement
K	MM	100.0%	100.0%	0%
P	MM	87.5%	100.0%	0%
U	MM	0.0%	100.0%	0%
Y	MM	100.0%	100.0%	0%
Z	MM	99.0%	100.0%	0%

The comparison with system reference is not done for this variable, because it gives no extra information.

The average and standard deviation of Height for system categories and reference is presented in Figure 60.

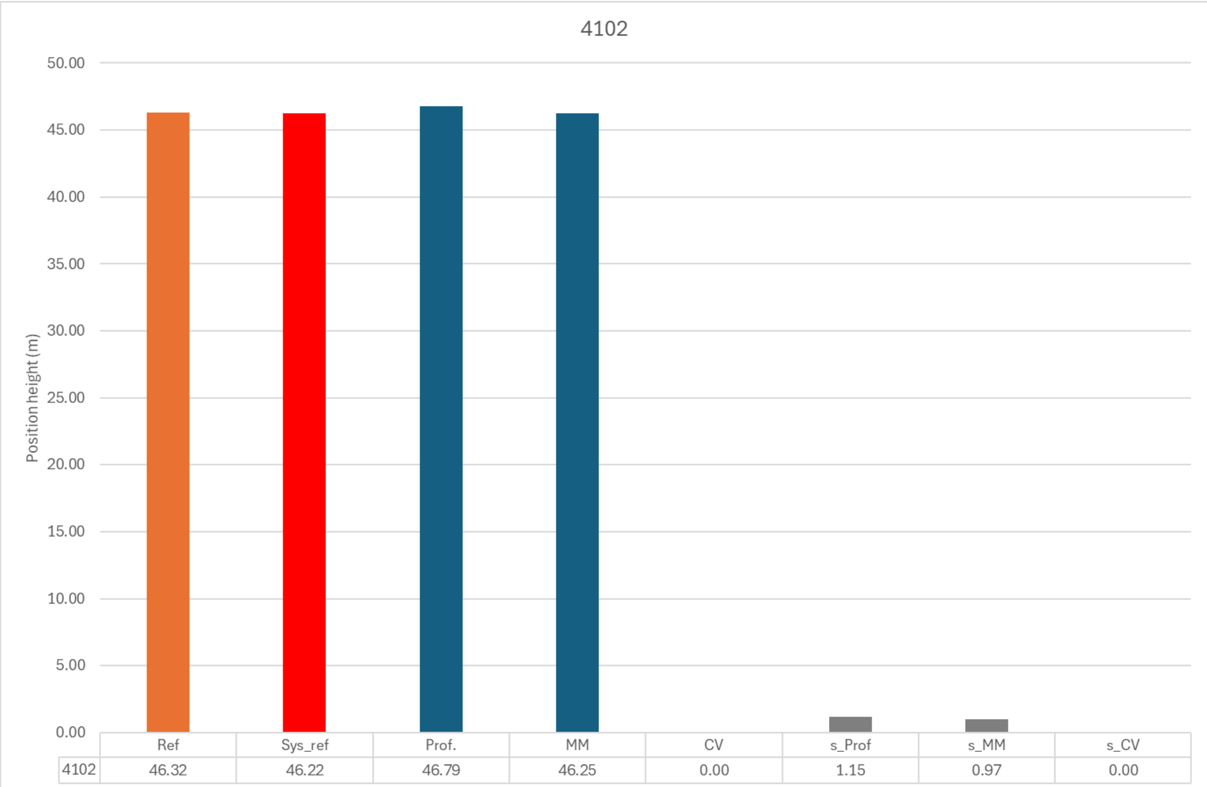


Figure 60 Overall average and standard deviation of Height.

A more detailed comparison, at 20 m level, between the reference and the average of the repeated runs for the participant categories can be seen in Figure 61.

Figure 61 Height, 20 m comparison between references and the average of the two participant categories.

The individual participants' average results for the two categories compared with the reference can be seen in Figure 62 and Figure 63.

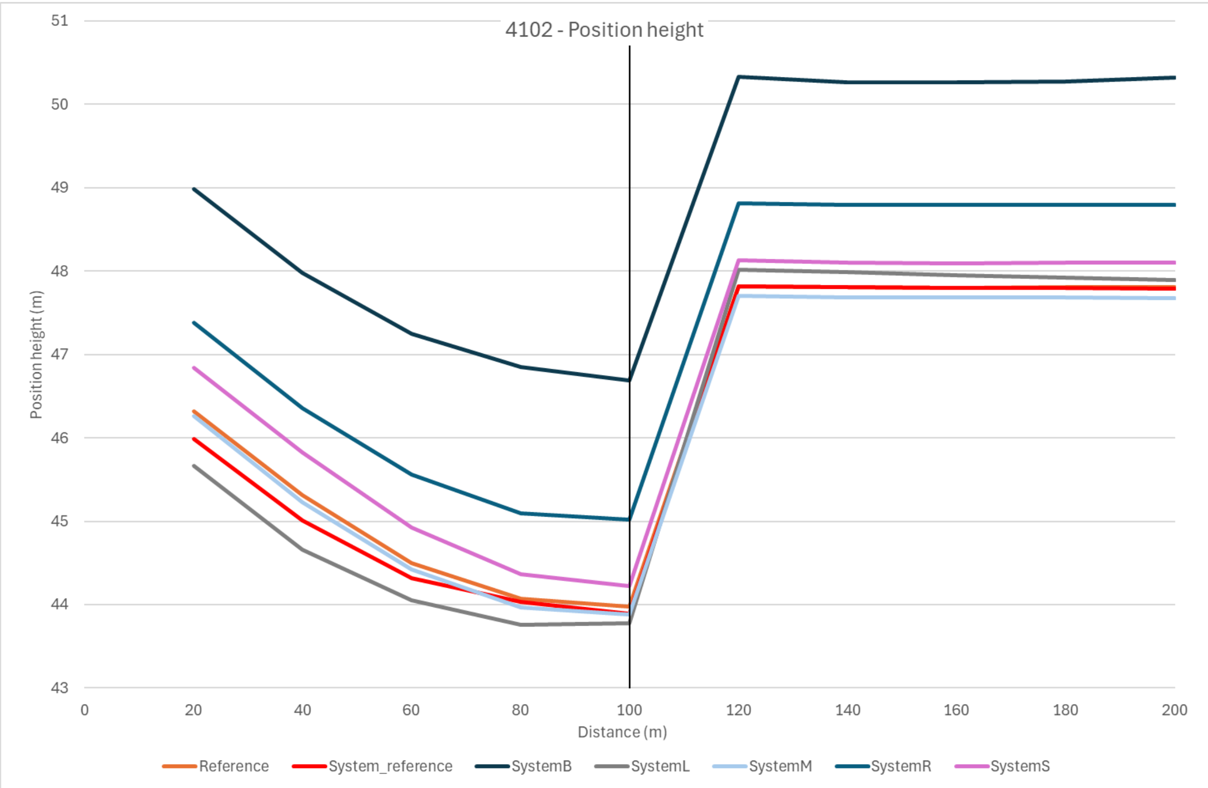


Figure 62 Height: comparison of reference values with each participant's average in the profilometer category.

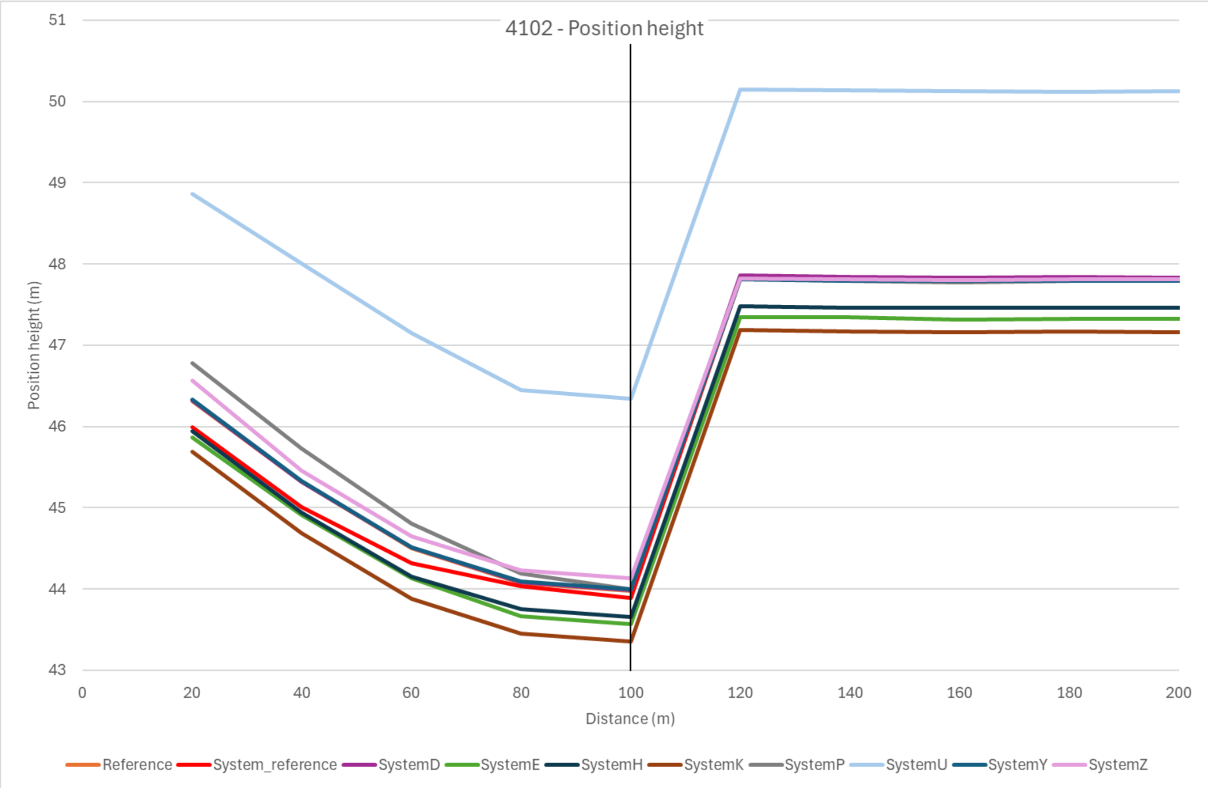


Figure 63 Height: comparison of reference values with each participant's average in the mobile mapping category.

9.2. Repeatability

Repeatability is tested according to chapter 6.1.2. The data is compiled into tables, showing 75th percentile of the 20 m standard deviations of the repeated runs.

9.2.1. TermID 1287 – IRI right wheel track

In total, 21 systems reported IRI data. The repeatability requirement used for profilometer measurements in Sweden for this variable is 0.2 mm/m. The result is compiled in Table 28.

Table 28 Results of the repeatability test for IRI in the right wheel track.

System	Category	Repeatability (mm/m)	Requirement (mm/m)
B	P	0.23	0.2
J	P	0.11	0.2
L	P	1.00	0.2
M	P	0.20	0.2
O	P	0.21	0.2
Q	P	1.35	0.2
R	P	0.14	0.2
S	P	0.21	0.2
D	MM	0.16	0.2
E	MM	0.14	0.2

System	Category	Repeatability (mm/m)	Requirement (mm/m)
H	MM	0.13	0.2
K	MM	0.11	0.2
P	MM	2.05	0.2
U[3]	MM	0.00	0.2
Y	MM	0.12	0.2
Z	MM	0.23	0.2
A	CV	0.91	0.2
N	CV	0.94	0.2
W	CV	0.31	0.2
X	CV	0.55	0.2

9.2.2. TermID 1025 – Rut Depth 3.2 m

In total, 13 systems reported Rut Depth 3.2 m data. The repeatability requirement used for profilometer measurements in Sweden for this variable is 0.5 mm. The result is compiled in Table 29.

Table 29 Results of the repeatability test for Rut Depth 3.2 m width.

System	Category	Repeatability (mm)	Requirement (mm)
J	P	0.17	0.5
L	P	0.32	0.5
M	P	0.14	0.5
O	P	0.22	0.5
R	P	0.14	0.5
S	P	0.14	0.5
D	MM	0.13	0.5
E	MM	0.15	0.5
H	MM	0.11	0.5
K	MM	0.13	0.5
P	MM	0.12	0.5
U[4]	MM	0.00	0.5
Y	MM	0.10	0.5

[3] One measurement delivered.

[4] One measurement delivered.

9.2.3. TermID 1035 – Sliding Wire Rut Depth 2,0 m

In total, 10 systems reported Sliding Wire Rut Depth 2.0 m data. The repeatability requirement used for profilometer measurements should be the same as for Rut Depth 3.2 m, 0.5 mm. This variable produces more consistent results than Rut Depth 3.2 m, as its method searches for the maximum rut depth within the measured width. However, the recorded Sliding Wire Rut Depth value is a lower estimate of the rut depth than the Rut Depth 3.2 m. The result is compiled in Table 30.

Table 30 Results of the repeatability test for Sliding Wire Rut Depth 2.0 m width.

System	Category	Repeatability (mm)	Requirement (mm)
L	P	0.24	0.5
M	P	0.12	0.5
O	P	0.28	0.5
S	P	0.1	0.5
D	MM	0.09	0.5
E	MM	0.11	0.5
K	MM	0.1	0.5
U	MM	0	0.5
Y	MM	0.08	0.5
Z	MM	0.14	0.5

9.2.4. TermID 3000 – Crossfall regression 3.2 m

In total, 12 systems reported Crossfall regression data. The repeatability requirement used for profilometer measurements in Sweden for this variable is 0.2 %. The result is compiled in Table 31.

Table 31 Results of the repeatability test for Regression Crossfall 3.2 m width.

System	Category	Repeatability (%)	Requirement (%)
L	P	0.19	0.2
M	P	0.02	0.2
Q	P	0.28	0.2
R	P	0.04	0.2
S	P	0.04	0.2
D	MM	0.01	0.2
H	MM	0.03	0.2
K	MM	0.01	0.2
P	MM	0.04	0.2
U[2]	MM	0.00	0.2
Y	MM	0.01	0.2
Z	MM	0.05	0.2

9.2.5. TermID 3302 – MPD right wheel track

In total, 12 systems reported MPD data. The repeatability requirement used for profilometer measurements in Sweden for this variable is 0.1 mm. The result is compiled in Table 32.

Table 32 Results of the repeatability test for MPD in the right wheel track.

System	Category	Repeatability (mm)	Requirement (mm)
I	P	0.03	0.1
J	P	0.03	0.1
L	P	0.09	0.1
M	P	0.03	0.1
O	P	0.07	0.1
Q	P	0.04	0.1
R	P	0.03	0.1
S	P	0.03	0.1
T	P	0.03	0.1
E	MM	0.04	0.1
H	MM	0.03	0.1
P	MM	0.04	0.1

9.2.6. TermID 3109 – Megatexture right wheel track

In total, 3 systems reported Megatexture data. The repeatability requirement used for profilometer measurements in Sweden for this variable is 0.1 mm. The result is compiled in Table 33.

Table 33 Results of the repeatability test for Megatexture in the right wheel track.

System	Category	Repeatability (mm)	Requirement (mm)
J	P	0.02	0.1
M	P	0.02	0.1
R	P	0.02	0.1

9.2.7. TermID 3800 – WLPσ right wheel track

In total, 3 systems reported WLPσ data. There is no repeatability requirement used for profilometer measurements in Sweden for this variable. The requirement used is experimental. The result is compiled in Table 34.

Table 34 Results of the repeatability test for WLPσ in the right wheel track.

System	Category	Repeatability (mm)	Requirement (mm)
M	P	1.01	1.2
E	MM	0.39	1.2
Z	MM	1.44	1.2

9.2.8. TermID 3801 – WLPΔ right wheel track

In total, 3 systems reported WLPΔ data. There is no repeatability requirement used for profilometer measurements in Sweden for this variable. The requirement used is experimental. The result is compiled in Table 35.

Table 35 Results of the repeatability test for WLPΔ in the right wheel track.

System	Category	Repeatability (mm)	Requirement (mm)
M	P	4.94	8
E	MM	3.38	8
Z	MM	9.67	8

9.2.9. TermID 4100 (3020) – Position Latitude

Repeatability for Position Latitude. Repeatability is calculated from the delivered Latitude-data from the individual runs. The test section is mainly located in the south-north or north-south direction, meaning, the Latitude-data indicates error is in the longitudinal direction. Some participants delivered the same position for all repetitions. This gives repeatability equal to zero and does not reflect the variation of the result for the tested system. In total 17 systems delivered Position data, the result is compiled in Table 36.

Table 36 Results of the repeatability test for Position Latitude.

System	Category	Repeatability (m)	Requirement (m)
B	P	0.59	0.5
L	P	2.85	0.5
M	P	0.07	0.5
Q	P	1.14	0.5
R	P	0.07	0.5
S	P	0.81	0.5
D	MM	0.00	0.5
E	MM	0.07	0.5
H	MM	3.39	0.5
K	MM	0.00	0.5
P	MM	0.34	0.5
U	MM	0.00	0.5
Y	MM	0.00	0.5
Z	MM	0.05	0.5
A	CV	0.00	0.5
N	CV	0.32	0.5
X	CV	6.64	0.5

9.2.10. TermID 4101 (3021) – Position Longitude

Repeatability for Position Longitude. Repeatability is calculated from the delivered Longitude-data from the individual runs. The test section is mainly located in the south-north or north-south direction, meaning the Longitude-data indicates error is in the transversal direction. Some participants delivered the same position for all repetitions. This gives repeatability equal to zero and does not reflect the variation of the result for the tested system. In total 17 systems delivered Position data, the result is compiled in Table 37.

Table 37 Results of the repeatability test for Position Longitude.

System	Category	Repeatability (m)	Requirement (m)
B	P	0.36	0.5
L	P	0.80	0.5
M	P	0.09	0.5
Q	P	0.35	0.5
R	P	0.05	0.5
S	P	0.49	0.5
D	MM	0.00	0.5
E	MM	0.06	0.5
H	MM	0.11	0.5
K	MM	0.00	0.5
P	MM	0.23	0.5
U	MM	0.00	0.5
Y	MM	0.00	0.5
Z	MM	0.13	0.5
A	CV	0.00	0.5
N	CV	0.61	0.5
X	CV	1.30	0.5

9.2.11. TermID 4102 – Height

The reference Height is calculated from the total station in combination with stationary satellite receiver. A total of 13 systems provided height data. The repeatability of the height data is presented in Table 38.

Table 38 Results of the repeatability test for Height.

System	Category	Repeatability	Requirement
B	P	0.530	0.5
L	P	1.210	0.5
M	P	0.010	0.5
R	P	0.010	0.5
S	P	0.390	0.5

System	Category	Repeatability	Requirement
D	MM	0.010	0.5
E	MM	0.020	0.5
H	MM	0.080	0.5
K	MM	0.000	0.5
P	MM	0.730	0.5
U	MM	0.000	0.5
Y	MM	0.040	0.5
Z	MM	0.090	0.5

9.3. Speed Dependency

A key attribute of road monitoring variables is the ability to obtain consistent results regardless of differing measurement conditions. This chapter outlines the distinctions between two speeds that are similar. A greater speed differential was desired; however, due to the presence of bumps (high IRI values) on section A, achieving this objective was not possible. Additional tests were conducted during a stop-and-go sequence, which are detailed in chapter 9.4.

The results are shown in three tables by system category. For variables with both positive and negative values, only absolute differences are listed. Also, position variables are presented only with an absolute difference. For other variables, both the ratio between measurements at higher and lower speeds and the absolute difference is provided[5]. The ratio is interpreted as follows: a value of 1.000 signifies no difference, whereas a value greater than 1 denotes an increase at higher speeds. Systems for which all measurements were conducted at a single speed are excluded from the tables.

In Finland, speed dependency thresholds in technical tests are 0.2 mm for rut depth and 0.1 mm/m for IRI. Further threshold values are listed in Annex 1.

[5] Example, Table 39, System L, Rut depth 3.2 m, the result 1.00/0.02 should be interpreted as: the quota between the higher and lower speed is 1.00 and the absolute value of the average difference between the two speeds is 0.02 mm.

The first system category presented is profilometer, see Table 39, followed of the categories for mobile mapping (Table 40) and connected vehicle (Table 41).

Table 39 Speed dependency for the profilometer category[5].

Variable	B	I	L	M	O	Q	R	S	T
Rut depth 3.2 m (mm)			1.00/ 0.02	1.01/ 0.05	1.00/ 0.01		0.99/ 0.03	0.98/ 0.05	
Sliding Wire Rut depth 2.0 m (mm)			1.01/ 0.04	1.01/ 0.03	1.03/ 0.08			0.90/ 0.16	
IRI, right (mm/m)	1.01/ 0.02		0.97/ 0.08	1.01/ 0.01	0.99/ 0.02	0.86/ 0.29	0.98/ 0.04	0.99/ 0.03	
MPD, right (mm)		1.00/ 0.00	1.02/ 0.02	1.00/ 0.00	1.02/ 0.03	1.03/ 0.03	1.01/ 0.01	1.00/ 0.00	1.00/ 0.00
Hilliness (%)			0.00	0.01		0.04	0.02		
Regression crossfall (%)			0.01	0.02		0.05	0.01	0.01	
Mega texture, right (mm)				0.98/ 0.01			1.00/ 0.00		
Position, S-N (m)	0.13		6.66	0.02		0.40	0.01	0.77	
Position, E-W (m)	0.25		1.00	0.00		0.24	0.01	0.62	
Height (m)	0.14		1.13	0.01			0.01	0.46	
Delta WLP (mm)				1.03/ 0.21					
Sigma WLP (mm)				1.04/ 1.18					

Table 40 Speed dependency for the mobile mapping category.

Variable	D	E	H	K	P	Y	Z
Rut depth 3.2 m (mm)	0.97/0.07	0.97/0.12	0.97/0.13	0.99/0.06	0.99/0.02	1.03/0.09	
Sliding Wire Rut depth 2.0 m (mm)	0.99/0.02	0.99/0.05		0.98/0.06		1.05/0.09	0.98/0.06
IRI, right (mm/m)	0.98/0.04	1.01/0.01	1.00/0.01	0.99/0.02	1.10/0.16	1.01/0.02	0.97/0.07
MPD, right (mm)		1.07/0.12	1.00/0.00		1.01/0.02		
Hilliness (%)	0.00	0.00		0.00	0.00	0.00	0.01
Regression crossfall (%)	0.00		0.02	0.00	0.00	0.00	0.02
Mega texture, right (mm)							
Position, S-N (m)	0.00	0.15	0.01	0.00	0.29	0.00	0.00
Position, E-W (m)	0.00	0.02	0.00	0.00	0.16	0.00	0.16
Height (m)	0.02	0.02	0.05	0.00	1.22	0.01	0.15
Delta WLP (mm)		0.97/0.13					1.04/0.27
Sigma WLP (mm)		0.98/0.42					1.09/3.30

Table 41 Speed dependency for the connected vehicle category.

Variable	A	N	W	X
Rut depth 3.2 m (mm)				
Sliding Wire Rut depth 2.0 m (mm)				
IRI, right (mm/m)	0.90/0.28	1.22/0.44	1.01/0.01	1.03/0.08
MPD, right (mm)				
Hilliness (%)				
Regression crossfall (%)				
Mega texture, right (mm)				
Position, S-N (m)	0.00	0.27		0.54
Position, E-W (m)	0.00	0.74		0.11
Height (m)				
Delta WLP (mm)				
Sigma WLP (mm)				

Systems in all categories are performing well, with low influence of speed.

9.4. Stop-and-Go

Seven systems choose to participate in the Stop-and-Go evaluation. The mobile mapping systems (D, K, Y) show very little dependence on the stop-and-go sequence at approximately 150 meters, whereas profilometers and connected vehicles and smartphones systems clearly are affected.

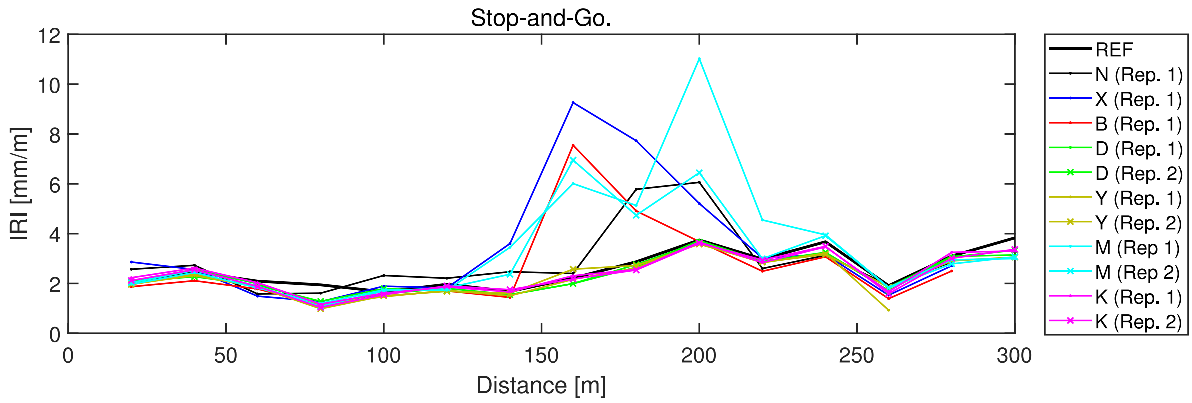


Figure 64 IRI results from the Stop-and-Go test.

9.5. Longitudinal Profile Power Spectral Density

The Power Spectral Density (PSD) is estimated using the Welch method (Welch, 1967) and a 99% overlap. For illustration, the PSDs are smoothed using the algorithm described in ISO 8608 (ISO, 2016). Profilometers are drawn with a solid line without marker, mobile mapping systems have a dot marker and connected vehicles and smartphone systems have a star marker.

Two systems (P and S) delivered high-pass filtered longitudinal profiles with little information above the 10-meter wavelength. Other systems (across all three categories) have little information in the texture domain (1 meter wavelength and below). Interestingly, all systems produce the same results between, approximately the wavelengths 4 and 10 meter. The PSD-results from the three sections can be seen in Figure 65 to Figure 67.

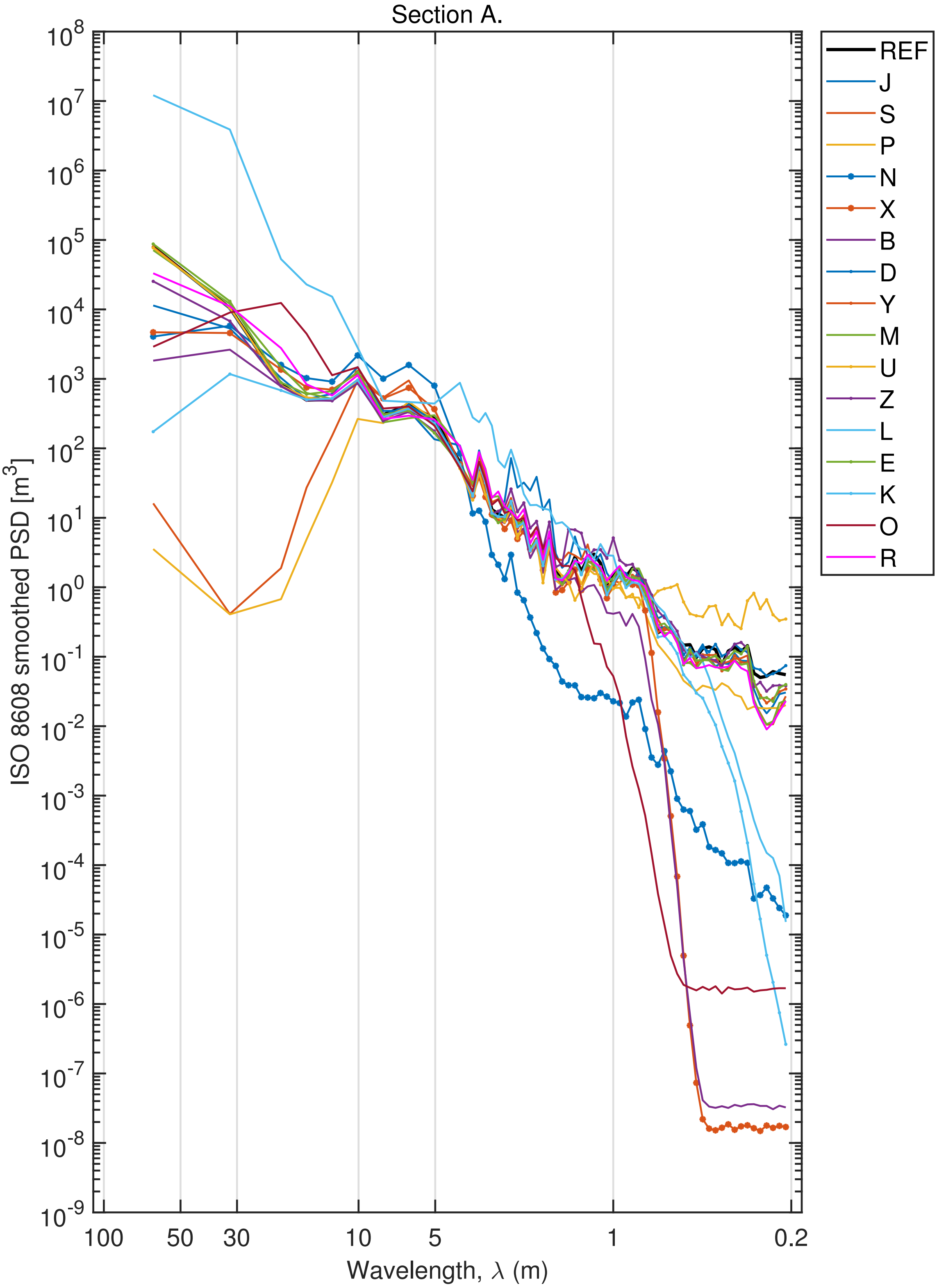


Figure 65 Results from PSD-analysis of the longitudinal profiles form section A.

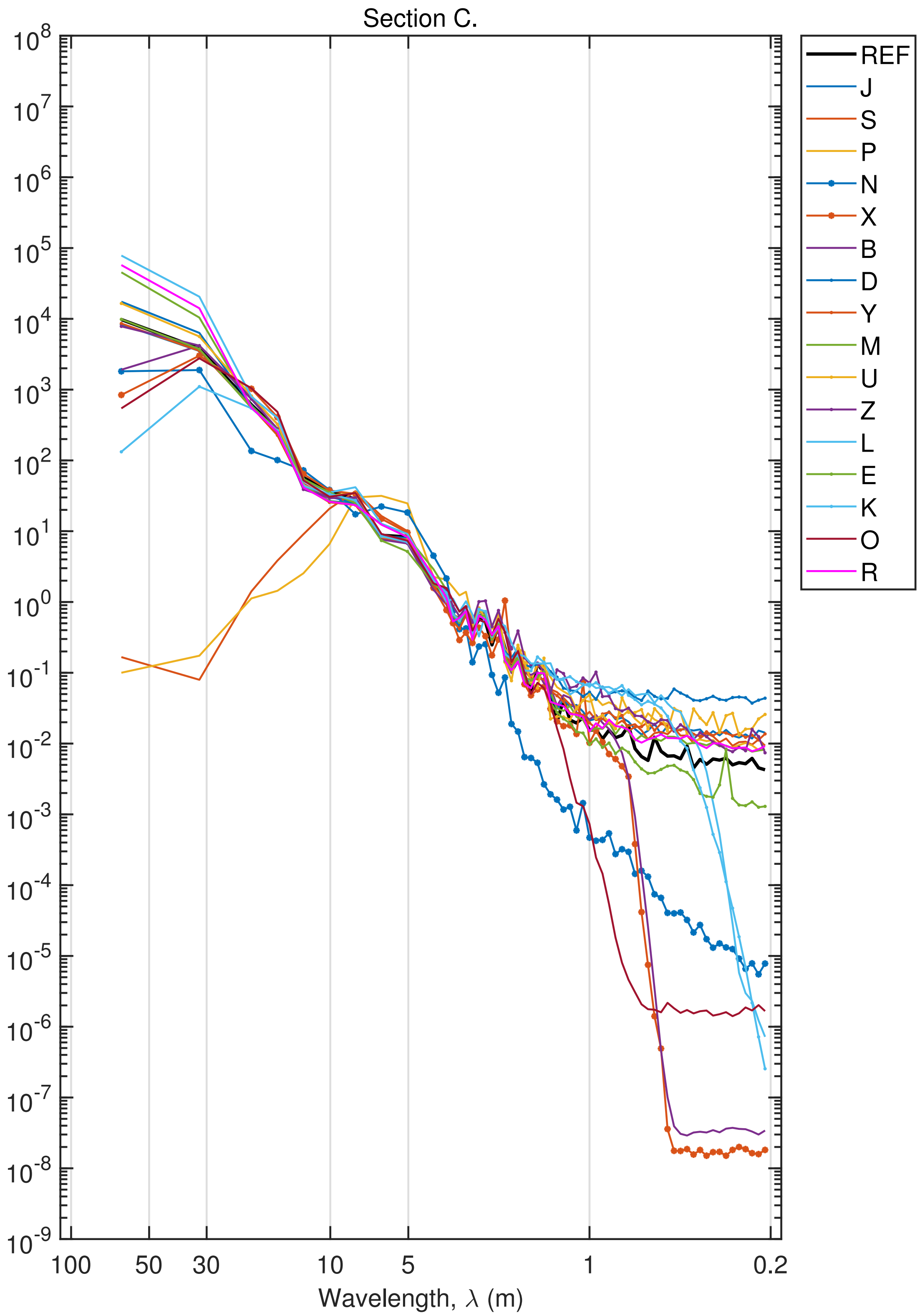


Figure 66 Results from PSD-analysis of the longitudinal profiles form section C.

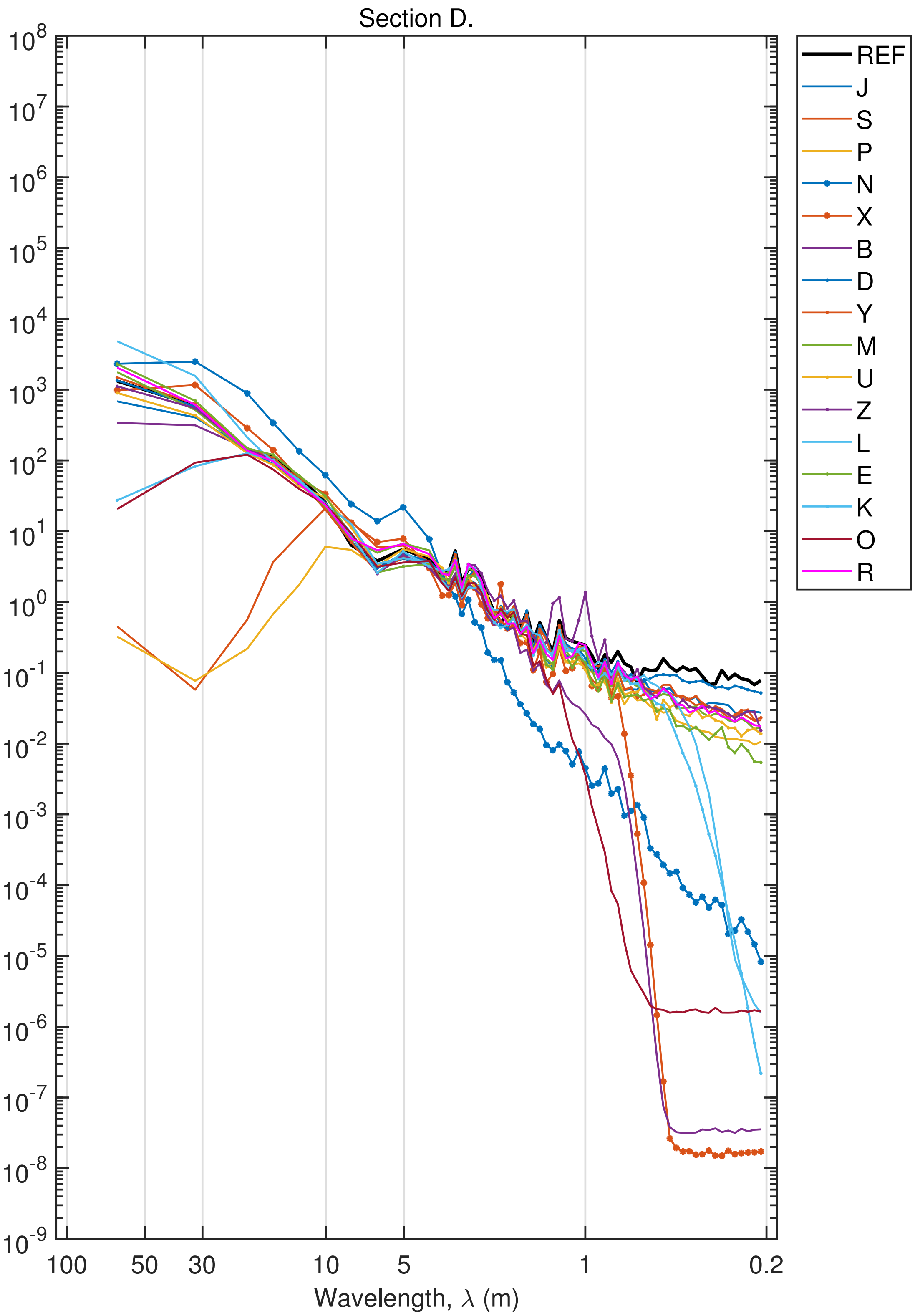


Figure 67 Results from PSD-analysis of the longitudinal profiles form section D.

For easier quantification than the rather cluttered figures above the quotient between the supplier and reference PSD are presented in Table 42. We have used the bi-octave bands from EN 13036-5:2019 (CEN, 2019), where long wavelengths (LW) are defined as 11.312 to 45.248 meters, medium wavelengths (MW) between 2.828 and 11.312 meters, and short wavelengths between 0.707 and 2.828 meters. We added the extra short wavelengths (XSW) between 0.2 and 0.707 to cover the interesting megatexture wavelengths.

An example of the data used to make the table is given in Figure 68. Note that the XSW band nicely extends the bi-octave succession. A quota near 1 (10^0) shows similar power in the frequency bands of participant and reference longitudinal profiles.

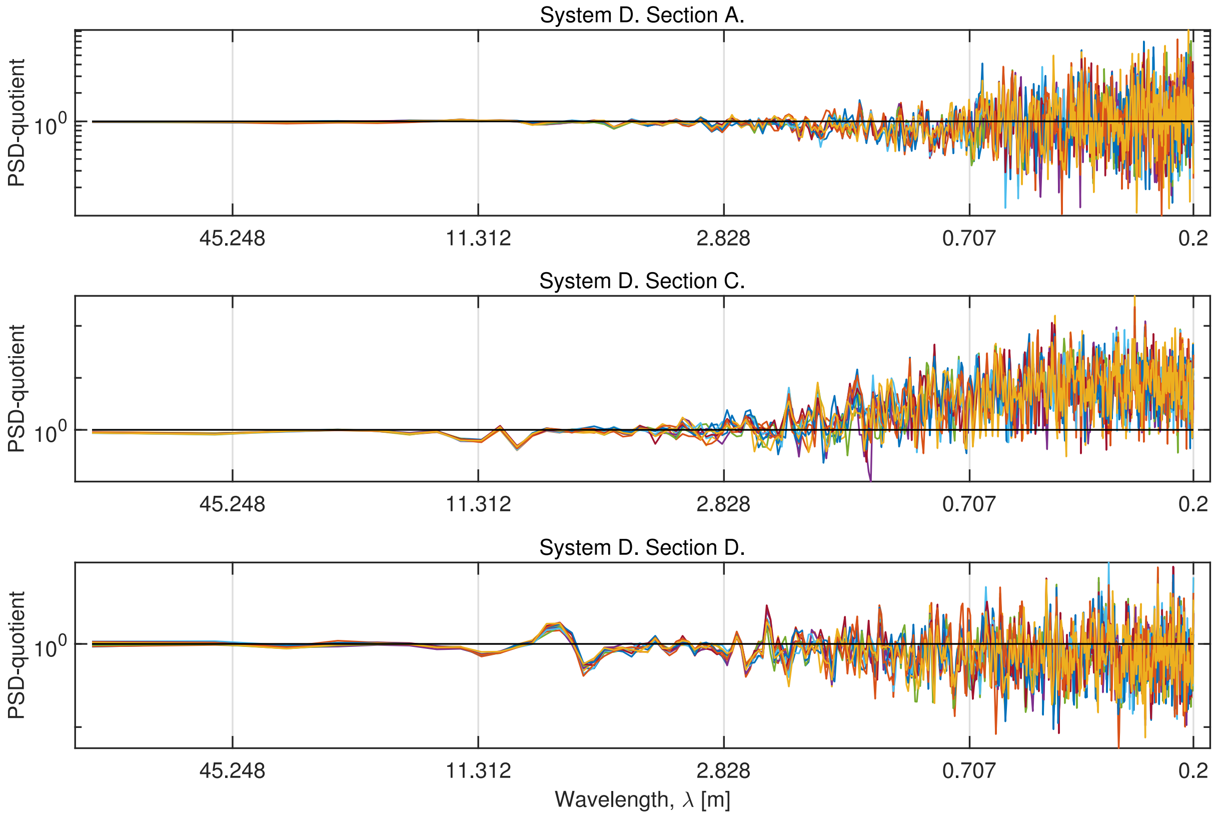


Figure 68 The PSD quotas between the participant and reference from the three sections used for evenness.

Table 42 presents the numerical details of the PSD quotas, with quotas listed individually for each system and section. This table facilitates the identification of how the systems cover wavelengths pertinent to assessing evenness. Figure 69 (Karamihas & Arbor, 2021) illustrates the temporal frequency response of the IRI algorithm, showing slope (spatial velocity across the suspension) in relation to slope spectral density. The wavelength axis corresponds with the standard Golden-Car simulation speed for the IRI at 80 km/h. IRI exhibits sensitivity to evenness within the frequency range of approximately 0.5 to 30 meters, with peak gain in the transfer function observed at around 2.3 and 15.8 meters.

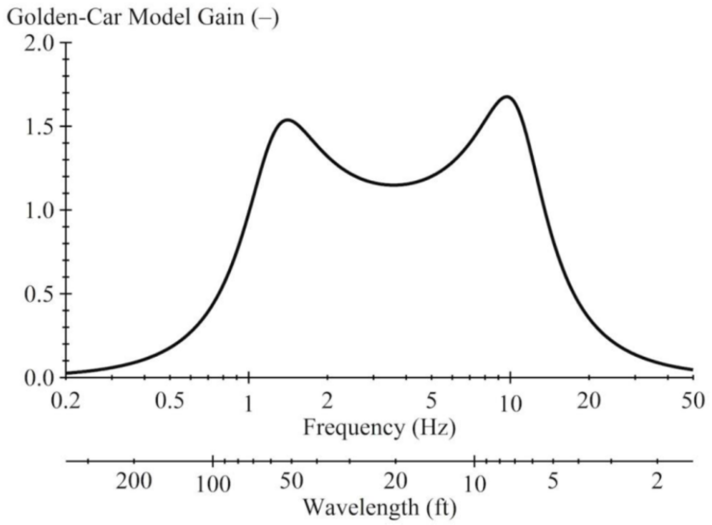


Figure 69 The temporal frequency response of the IRI algorithm (Karamihas & Arbor, 2021).

The MW frequency band plays an important role in calculating IRI because it includes wavelengths with a transfer function gain greater than 1. Additionally, wavelengths found in the LW band are significant, as they generally contain much more energy than those in the MW and SW bands.

Table 42 PSD quotas between the participant and reference divided into four wavelength bands.

System	Section	LW	MW	SW	XSW	System	Section	LW	MW	SW	XSW
J	A	1.039	1.205	2.002	0.806	M	A	1.276	1.267	1.077	0.635
J	C	1.074	1.070	1.794	2.241	M	C	1.390	1.214	1.179	1.518
J	D	0.991	0.998	1.464	1.667	M	D	1.218	1.195	1.041	1.144
S	A	0.135	1.348	1.179	0.705	U	A	1.018	0.872	0.831	6.829
S	C	0.105	1.257	1.411	1.840	U	C	1.089	0.945	1.376	6.194
S	D	0.102	1.250	1.263	1.387	U	D	0.997	0.978	1.131	4.238
P	A	0.029	0.868	0.681	0.391	Z	A	0.906	0.873	1.903	1.067
P	C	0.025	1.419	1.546	1.688	Z	C	0.924	0.936	2.715	2.165
P	D	0.023	1.188	1.254	1.201	Z	D	0.922	0.917	2.408	1.599
N	A	1.605	2.001	0.034	0.003	L	A	160.511	8.153	2.587	0.389
N	C	1.138	1.843	0.066	0.005	L	C	81.551	4.755	3.272	1.412
N	D	2.178	2.069	0.066	0.004	L	D	54.863	3.489	2.500	1.011
X	A	1.246	1.269	0.730	0.004	E	A	1.235	0.934	0.909	0.881
X	C	1.184	1.138	0.890	0.005	E	C	1.101	0.919	0.899	0.796
X	D	1.355	1.148	0.791	0.004	E	D	1.114	0.898	0.800	0.589
B	A	0.815	0.877	0.452	0.002	K	A	0.728	0.937	0.840	0.149
B	C	0.906	0.886	0.929	0.005	K	C	0.685	0.963	2.330	0.816
B	D	0.871	0.873	0.712	0.003	K	D	0.676	0.951	1.820	0.587
D	A	1.000	0.957	0.886	1.264	O	A	5.612	1.098	0.517	0.000
D	C	0.923	0.948	2.133	6.381	O	C	3.340	1.110	0.487	0.000

System	Section	LW	MW	SW	XSW	System	Section	LW	MW	SW	XSW
D	D	0.929	0.946	1.721	4.566	O	D	2.420	1.029	0.422	0.000
Y	A	1.000	0.884	0.877	0.759	R	A	1.791	1.300	1.139	0.593
Y	C	0.914	0.865	1.238	2.318	R	C	1.805	1.178	1.219	1.543
Y	D	0.932	0.866	1.077	1.721	R	D	1.517	1.173	1.089	1.168

9.6. Positions of Objects

Five objects. For each system, the objects (cones) are numbered from 1 to 5. Figure 70 is an overview, which shows that a few systems consistently report a position off by about one meter. This is almost certainly a problem with coordinate transformations, and not the actual accuracy of these systems. The detailed right image (Figure 71) shows that some systems delivered data with very high accuracy.

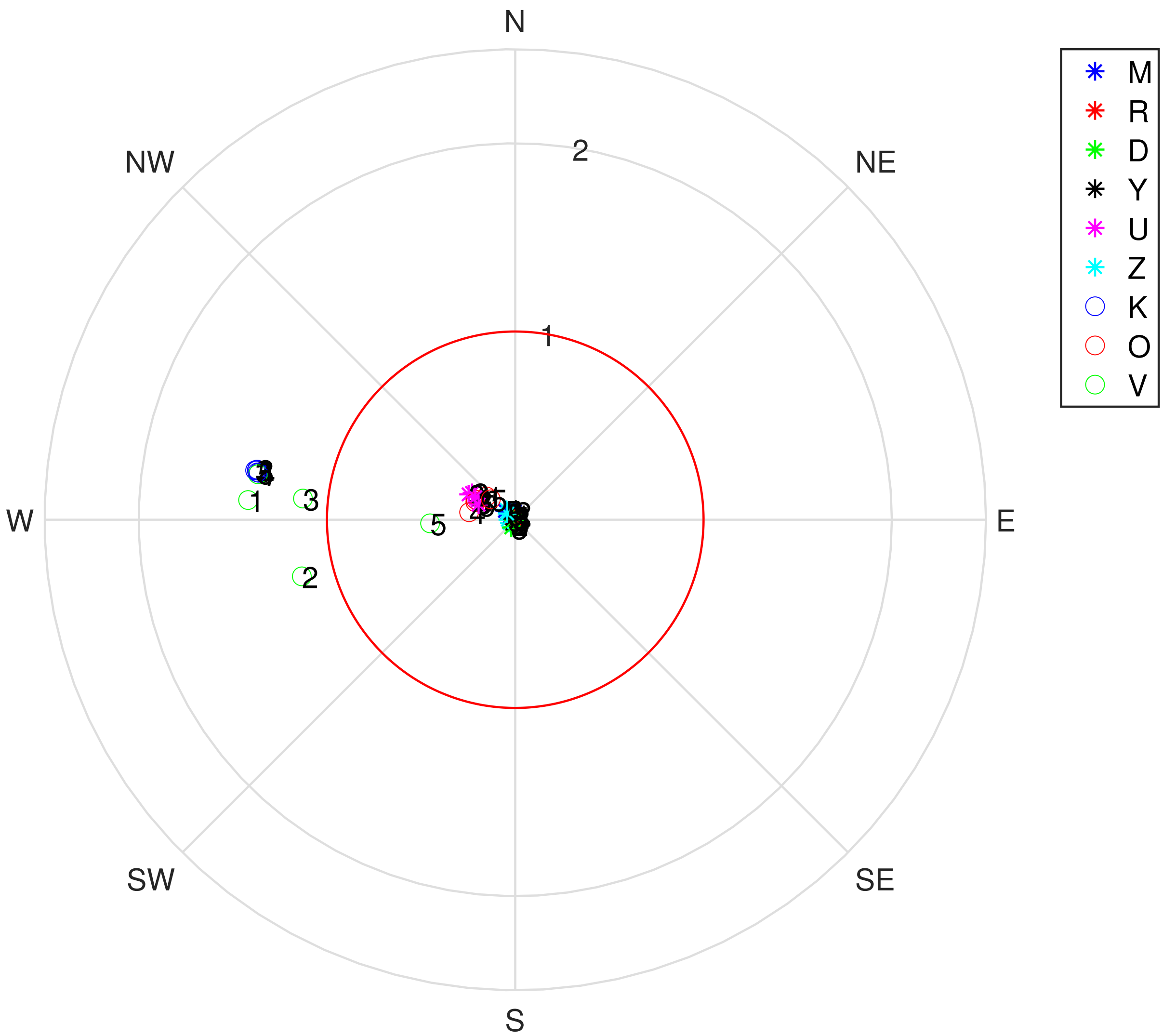


Figure 70 Distance from reference for the positioning of object test. The scale 0 to 2.5 in the polar plot is meter.

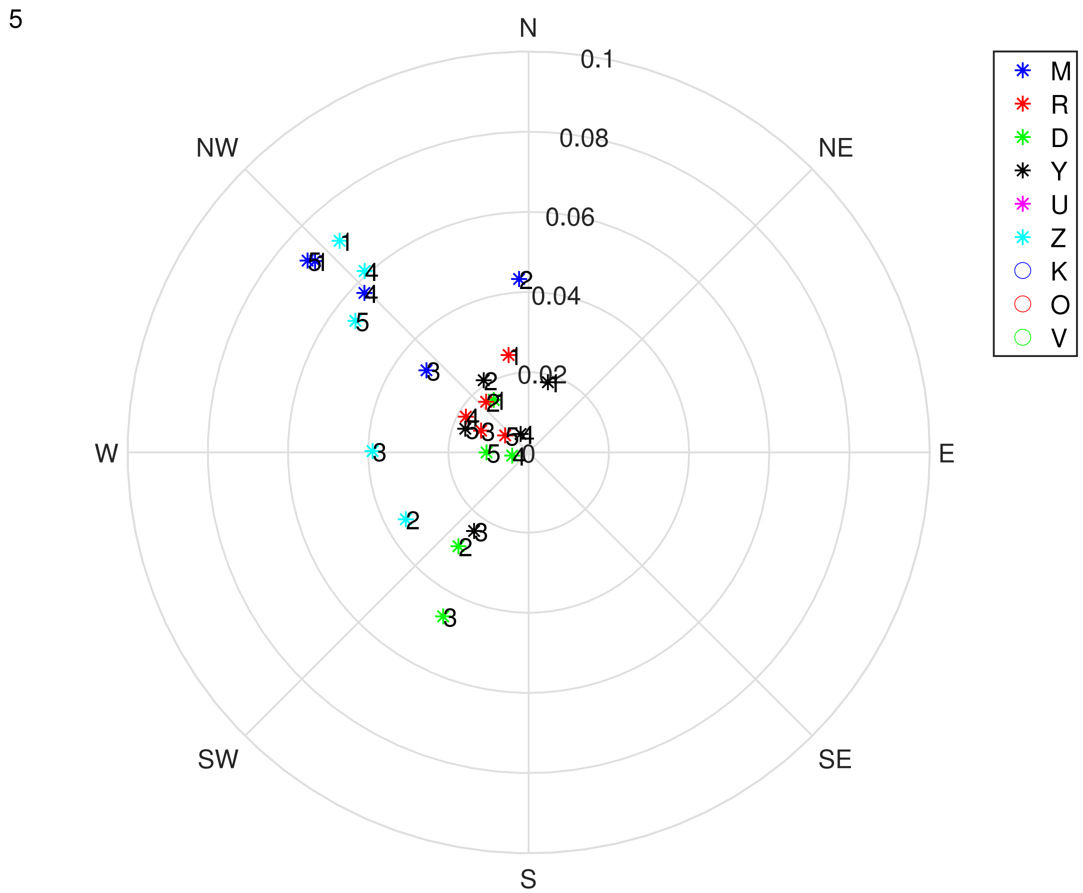


Figure 71 Distance from reference for the positioning of object test. The scale 0 to 0.1 in the polar plot is meter.

A more detailed presentation of the agreement between the participant positioning of the five cones and the reference can be seen in Table 43 to Table 47. The symbols in the tables are explained below.

Pos. diff. latitude/longitude average difference

Pos. std. the standard deviation of the latitude/longitude difference between the repeated runs

H diff. height average difference

H std. the standard deviation of the height difference between the repeated runs

Reps. The number of repetitions delivered/analyzed

Table 43 The results from positioning cone 1.

System	Pos. diff. (m)	Pos. std. (m)	H diff (m)	H std. (m)	Reps.
M	0.07	0.01	-0.05	0.01	10
R	0.03	0.01	0.25	0.01	10
D	0.02	0.01	0.05	0.02	10
Y	0.02	0.01	0.00	0.02	10
U	0.22		0.01		1
Z	0.10	0.04	0.00	0.08	12
K	1.40	0.00	-0.61	0.00	10
O	0.20		0.68		1
V	1.43	1.11			2

Table 44 The results from positioning cone 2.

System	Pos. diff. (m)	Pos. std. (m)	H diff (m)	H std. (m)	Reps.
M	0.01	0.01	-0.05	0.01	10
R	0.02	0.01	0.26	0.02	10
D	0.03	0.01	0.05	0.02	10
Y	0.02	0.01	0.01	0.02	10
U	0.27		0.01		1
Z	0.09	0.05	0.03	0.20	12
K	1.40	0.00	-0.62	0.00	10
O	0.24		0.69		1
V	1.34	0.48			4

Table 45 The results from positioning cone 3.

System	Pos. diff. (m)	Pos. std. (m)	H diff (m)	H std. (m)	Reps.
M	0.03	0.02	-0.05	0.01	10
R	0.02	0.01	0.26	0.00	10
D	0.05	0.00	0.05	0.01	10
Y	0.03	0.01	0.00	0.02	10
U	0.28		0.00		1
Z	0.07	0.05	0.07	0.09	12
K	1.41	0.00	-0.63	0.00	10
O	0.23		0.74		1
V	1.36	0.33			3

Table 46 The results from positioning cone 4.

System	Pos. diff. (m)	Pos. std. (m)	H diff (m)	H std. (m)	Reps.
M	0.06	0.02	-0.04	0.01	10
R	0.02	0.01	0.23	0.01	10
D	0.01	0.01	0.05	0.01	10
Y	0.01	0.01	0.00	0.02	10
U	0.24		0.01		1
Z	0.09	0.06	0.00	0.09	12
K	1.38	0.00	-0.63	0.00	10
O	0.25		0.69		1
V	1.42	0.59			3

Table 47 The results from positioning cone 5.

System	Pos. diff. (m)	Pos. std. (m)	H diff (m)	H std. (m)	Reps.
M	0.07	0.01	-0.04	0.01	10
R	0.01	0.01	0.26	0.01	10

System	Pos. diff. (m)	Pos. std. (m)	H diff (m)	H std. (m)	Reps.
D	0.01	0.01	0.05	0.01	10
Y	0.02	0.01	0.00	0.02	10
U	0.21		0.01		1
Z	0.07	0.06	0.00	0.09	12
K	1.39	0.00	-0.64	0.00	10
O	0.17		0.68		1
V	0.78	0.01			2

9.7. Wide transversal profiles

Seven systems supplied wide transversal profiles. The transversal profiles from System U didn't cover the full six meters so the profiles have been translated to have the end points fixed on the reference profile. As no indexes have been calculated we refer to the graphs in Figure 72 for evaluation.

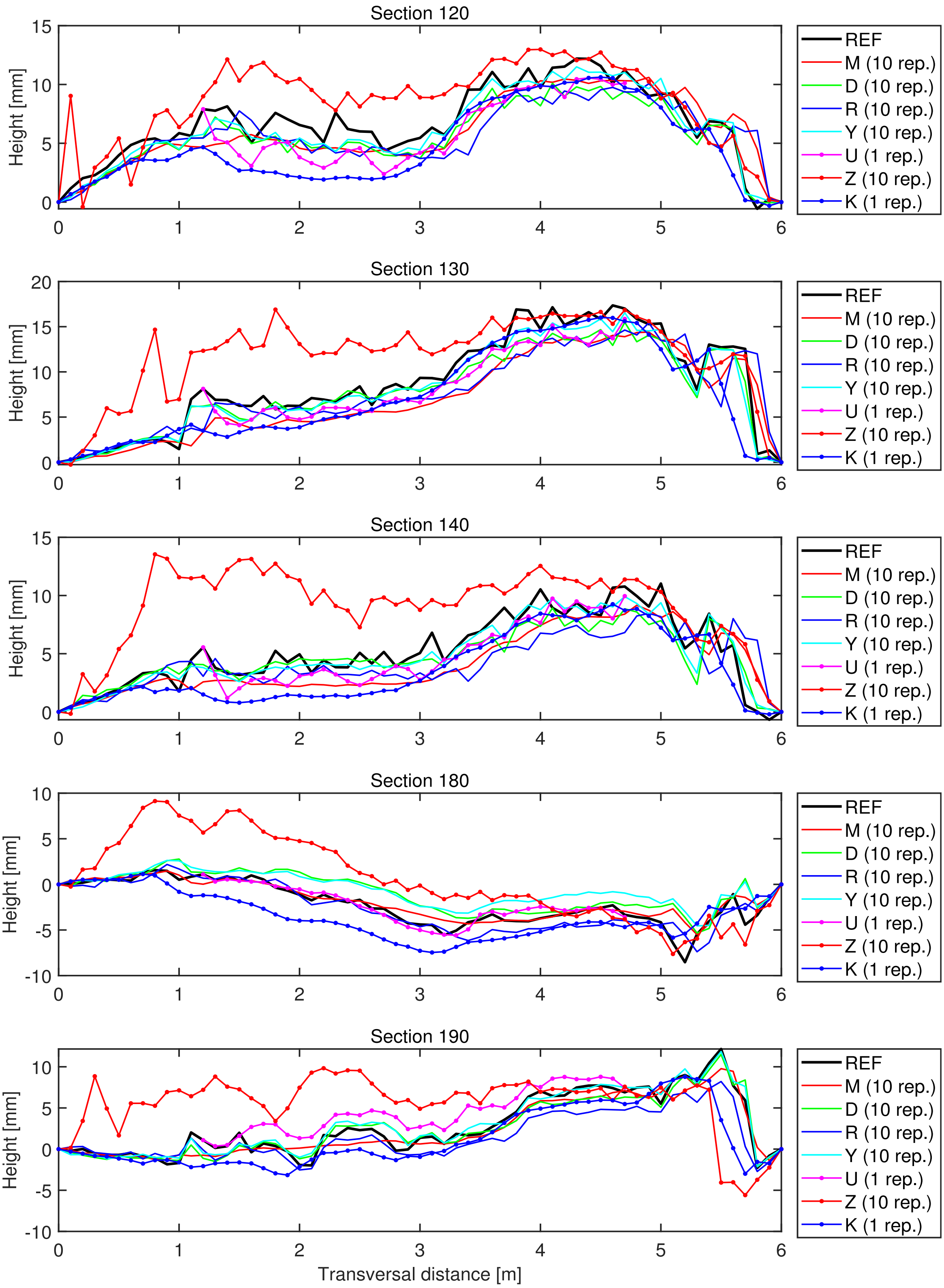


Figure 72 Wide (six meters) transversal profiles on test section D.

9.8. Cracks

Four systems delivered data on the cracks from test section B. The cracks proved to be difficult for the automated systems, and a simplified method of evaluation was used. Instead of evaluating the five zones an average across the width of the road was used. As can be seen in Figure 73 all four systems correlate with the reference.

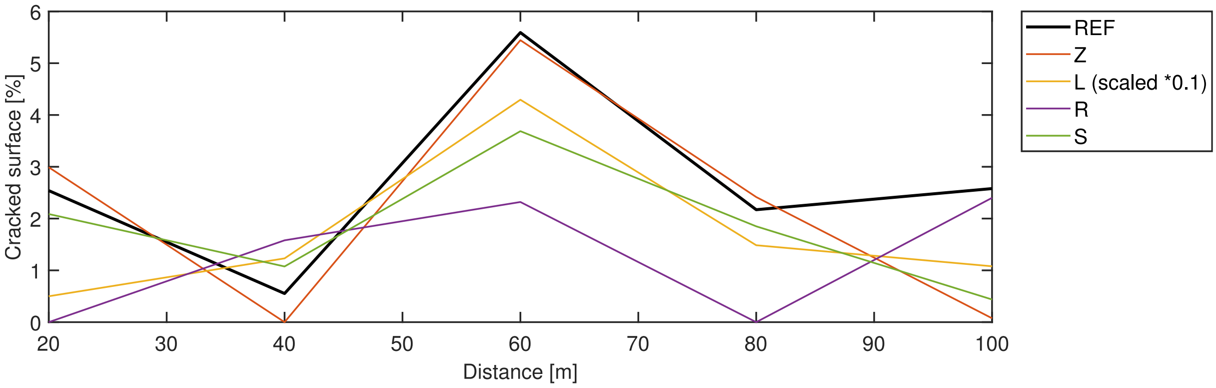
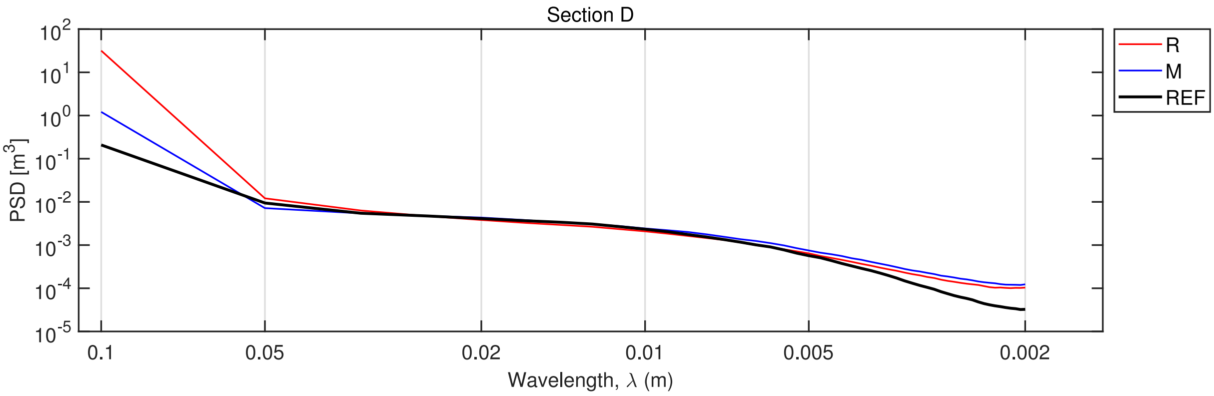


Figure 73 Results from the crack detection on test section B.

9.9. Texture Power Spectral Density

Only two systems delivered texture profile data, with very similar results. The somewhat lower "energy" levels for the reference equipment might be a smoothing effect from its short sampling distance.



9.10. Longitudinal Profile Repeatability Check

In the longitudinal profile repeatability check the profile from repetition 1 is compared to the profiles from repetition 2 and up, then the profile from repetition 2 is compared to the profiles from repetitions 3 and up, and so on. A typical example of a comparison after the synchronization is given in Figure 74. The longitudinal profiles are high-pass filtered at 30 meters. The test criteria are described in chapter 7.1.3.

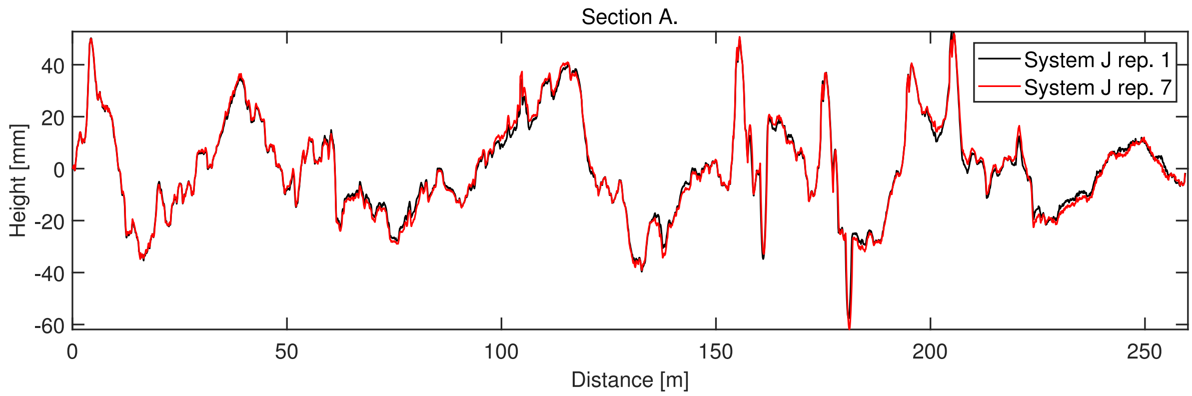


Figure 74 Example of longitudinal profile repeatability check.

The results of the longitudinal profile check can be seen in Table 48. Below are the columns in the table described.

Corr – the average correlation between all repetitions
Corr lim 1 – % of result above the Swedish requirements (approval Corr limit 80)
Corr lim 1 – % of result above experimental requirements (Corr limit 90)
Stdq – the average of the quotas between the standard deviations
Stdq lim 1 – % of result above the Swedish requirements (approval Stdq limit 80)
Stdq lim 2 – % of result above experimental requirements (Stdq limit 90)

A test of suppliers in Sweden should have results above 80 % in the columns "Corr lim 1" and "Stdq lim 1".

Table 48 Results from the longitudinal profile quality check.

System	Corr	Corr lim 1 (%)	Corr lim 2 (%)	Stdq	Stdq lim 1 (%)	Stdq lim 2 (%)
B	0.96	99.63	92.22	0.94	99.26	78.89
J	0.99	100.00	100.00	0.97	100.00	97.62
L	0.93	92.26	73.81	0.90	93.45	70.83
M	0.97	100.00	99.63	0.96	100.00	92.59
O	0.97	100.00	95.83	0.93	91.67	82.14
R	0.98	100.00	100.00	0.97	100.00	100.00
S	0.93	94.05	79.76	0.95	100.00	83.93
D	0.98	100.00	100.00	0.99	100.00	100.00
E	0.97	100.00	94.44	0.93	97.62	73.49
K	0.99	100.00	100.00	0.99	100.00	100.00
P	0.90	83.93	72.62	0.91	91.67	86.31
Y	0.99	100.00	100.00	0.98	100.00	100.00
Z	0.97	100.00	100.00	0.96	100.00	94.81
N	0.72	39.13	10.37	0.84	71.22	45.24
X	0.79	56.72	32.00	0.81	67.95	43.06

9.11. Longitudinal Profile Validity Check

This test covers the closeness between the reference and participant longitudinal profile. For this test, the same method as for the longitudinal profile repeatability is used, but the supplier is compared to the reference. The same filtering that is done for the participants longitudinal profiles is done with the reference longitudinal profiles. An example of a synchronized participant profile and the reference from section D can be seen in Figure 75.

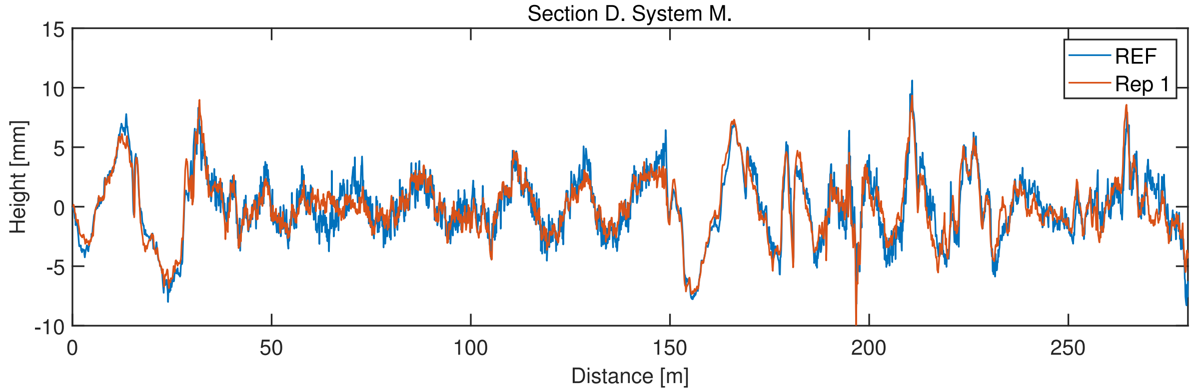


Figure 75 Example of longitudinal profile versus reference after the longitudinal alignment.

The table headers below are explained in the previous chapter. The longitudinal profile validity is not tested in Sweden; the limits are experimental.

Table 49 Results from the longitudinal profile quality check.

System	Corr	Corr lim 1 (%)	Corr lim 2 (%)	Stdq	Stdq lim 1 (%)	Stdq lim 2 (%)
B	0.96	99.63	92.22	0.94	99.26	78.89
J	0.99	100.00	100.00	0.97	100.00	97.62
L	1.08	92.66	75.11	0.89	91.74	69.31
M	0.97	100.00	99.63	0.96	100.00	92.59
O	0.97	100.00	95.83	0.93	91.67	82.14
P	0.90	83.93	72.62	0.91	91.67	86.31
R	0.98	100.00	100.00	0.97	100.00	100.00
S	0.93	94.05	79.76	0.95	100.00	83.93
D	0.98	100.00	100.00	0.99	100.00	100.00
E	0.97	100.00	94.44	0.93	97.62	73.49
K	0.99	100.00	100.00	0.99	100.00	100.00
Y	0.99	100.00	100.00	0.98	100.00	100.00
Z	0.97	100.00	100.00	0.96	100.00	94.81
N	0.80	41.11	12.59	0.85	72.22	45.93
X	0.94	59.26	35.65	0.81	68.52	41.67

9.12. Lane Width

The four road markings on section D were used to test the capability to measure lane width. The road markings were placed at four positions (represented by Pos 40, 60, 100 and 120 in Table 50). The table presents the average difference between the participant and reference in combination with the standard deviation. No standard deviation is given for the systems with only one repetition. Positive values represent greater participant values than the reference and the opposite for negative values.

Table 50 Average difference and standard deviation between reported lane width and reference.

	Pos 40		Pos 60		Pos 100		Pos 120	
System	Diff (mm)	Std (mm)	Diff (mm)	Std (mm)	Diff (mm)	Std (mm)	Diff (mm)	Std (mm)
L	-184.04	234.74	-182.15	167.50	-255.20	260.15	-298.29	286.71
M	-23.74	8.40	4.51	4.58	7.74	3.02	-9.45	4.07
O	-5.98		5.29		8.11		-9.97	
R	5.19	1.87	6.06	1.41	1.67	1.64	-0.84	2.51
D	-7.59	3.59	-6.20	6.13	-4.81	5.90	-4.83	7.56
E	-90.28	4.23	-126.15	0.94	-114.13	1.61	-131.86	1.27
K	10.92		9.09		4.31		1.83	
U	3.00		3.85		-1.36		-3.76	
Y	-1.65	5.11	-1.71	8.28	-5.16	6.80	-2.01	8.03
Z	-7.36	7.39	-6.55	3.17	-14.13	3.09	-18.08	3.65

10. Conclusions

The findings from duraBASt demonstrate participation from numerous advanced systems across all three examined categories: profilometers, mobile mapping, and connected vehicle and smartphone solutions. The data suggests that alternatives to traditional profilometers are now viable for evaluating road surface conditions. Mobile mapping technology, in particular, has evolved to the point where certain parameters can be captured with accuracy equal to or exceeding that of profilometers, as evidenced by this assessment. The maturity of this technology enables reliable measurements of road surface evenness in both longitudinal and transverse directions and exhibits relative insensitivity to variations in speed. These systems rely on satellite positioning supplemented by high-quality GNSS/INS equipment, which is essential for comprehensive measurement across entire road networks, including challenging environments such as tunnels, dense forest corridors, and urban areas. Current advancements in measurement vehicles are trending towards integrating profilometer functions with mobile mapping, thereby enabling simultaneous collection of conventional profilometer data and comprehensive road area mapping.

A summary of the results regarding validity, comparison with dedicated reference measurements, and the system's repeatability is shown in the following table (Table 51). The data have been cleaned before compilation, as the worst results in each category have been excluded (threshold: 25th percentile). The mobile mapping systems who delivered the same data from all repetitions is excluded from the repeatability average. The outcome after this exclusion better reflects the normal values from each category.

Table 51 Validity and repeatability: overall average results per category.

	Validity			**Repeatability**		
	P	**MM**	**CV**	**P**	**MM**	**CV**
IRI	73%	81%	50%	0.18	0.13	0.60
Rut depth 3.2m	79%	75%		0.15	0.12	
Sliding Wire Rut Depth 2.0m	74%	90%		0.15	0.09	
Crossfall Regression	96%	99%		0.07	0.02	
Hilliness	100%	100%		0.05	0.02	
MPD	70%	43%		0.03	0.04	
Latitude[6]	39%	87%		0.39	0.07	0.32
Longitude				0.21	0.09	0.61
Height	88%	100%		0.24	0.03	

Overall, the mobile mapping systems perform best in this test, this applies to both validity and repeatability. The systems with best performance in the profilometer category have results close to the results from the mobile mapping systems. The connected vehicle category has the poorer agreement with reference and poorer repeatability. This was expected; the systems are not as complex but on the other hand easy to use and to collect data frequently. The connected vehicle systems have often other agendas with the measurements, measurements are done at a road network not measured earlier in development countries, gravel roads or cities or at wintertime when normal road monitoring is not

[6] The longitude validity is not only done from the longitude, but as the difference between the reference and participants longitude and latitude.

suitable to do. To increase quality, crowd sourcing is used to get a lot of measurements at the same place.

At one of the sections the ability to give a correct IRI-value (International Roughness Index) while breaking-stopping-accelerating (stop-and-go). The stop-and-go test shows good results for the mobile mapping participants whereas profilometers and connected vehicles and smartphones systems clearly are affected.

The Power Spectrum Density of the Longitudinal Profiles shows the system ability to get information about the road surface in the wavelength band between 0.2 up to 100 meters. All systems have good agreement with the reference in the wavelength band 4 to 10 meters. Above and below these boundaries the agreement is poorer. Several systems have, however, good agreement through the whole spectrum. An additional test of the longitudinal profile has been done. The control method used in Sweden for repeatability are applied. The same method is also used for validity in this test. The repeatability results are generally good; most systems would meet the repeatability requirements used in Sweden. The comparison between the participant longitudinal profiles and the reference also shows good agreement.

Cracks have been difficult to analyze in detail. The reference has been compared with the participants measurement covering the complete measurement width, 3.8 meters, not as predetermined, in five zones. The results between reference and the participating systems are, however, good.

The task of positioning five objects in latitude, longitude and height shows very good results. Most systems could position the top of a cone within a few centimeters.

Finally, the participants' ability to measure a correct lane width were tested. Four temporary pairs of road markings were placed at one of the sections. The average distance between the road markings (18.75 meters long) was compared with reference measurement. Most systems manage to measure a "lane width" within 1 centimeter from the reference measurement. This must be considered very good and useful data.

11. Discussion

The duraBASt test was carried out in 2024 as part of a VTI initiative for the European road monitoring sector. The most recent test of this kind in Europe prior to duraBASt was the FILTER-test, conducted in the late 1990s (Descornet, et al., 2000; Willett, et al., 2000; Ducros, et al., 2001), with PIARC acting as the coordinator. Nearly 25 years have passed between these tests, which is far too long.

Over the past decade, the development rate of monitoring systems has accelerated significantly, resulting in denser data collection while maintaining high accuracy. For example, the traditional use of 17 to 25 point-lasers for measuring transverse evenness has been superseded by line laser sensors, which provide a near-continuous profile of the road surface and enable the assessment of cracks and surface defects. Although the number of measured variables has increased, it has not kept pace with the growth in collected data. There is a need to better convert this comprehensive description of road surfaces into actionable variables for maintenance planning.

One effective approach is to share insights at conferences such as ERPUG, and through open-source publications. If knowledge on variable extraction is restricted to a single company, it is unlikely to be widely adopted by road authorities for routine maintenance.

The ERPUG evaluation survey conducted after the 2024 Cologne conference included a question regarding interest in performing these tests regularly. The most popular response was “every two years”. However, it may be more appropriate to conduct these evaluations every five years to align with the anticipated advancement rate of measurement systems. Any future testing should be meticulously designed to encompass both standard and challenging measurement scenarios. The test sections should be chosen to span a full range of the tested variables to thoroughly assess system performance. Additionally, measurement speeds should cover typical traffic conditions, ideally within 30 to 80 km/h. Exploring longer test loops as a complement to shorter sections could further simulate real-world production environments. Longer loops evaluate the system’s production capacity using a methodology distinct from that of shorter test sections. This forms part of the technical testing process conducted in Sweden and Finland to qualify a supplier for network measurements. The supplier is required to demonstrate both strong repeatability and reproducibility.

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Annex 1. Threshold levels

The threshold levels are divided into “Standard threshold levels” and “Additional threshold levels”. The standard levels are used in Sweden or Finland in similar tests. The additional levels are new and/or experimental. The threshold levels are divided into two groups, 1 and 2. For instance, threshold level “IRI Right 1”, which can be found in Table 52, has a tighter tolerance than threshold level “IRI Right 2” (Table 53). The results from utilizing these threshold levels can be found in chapter 9. Group level 1 is presented as Validity_Ref1 and level 2 consequently as Validity_Ref2.

Validity

Standard threshold levels

This chapter describes threshold values used in Sweden and in this test.

TV – Tested Vehicle

Ref – Reference (could be dedicated reference measurements or system average)

Table 52 Standard threshold levels for the validity test.

Variable	Category	Acceptance interval
IRI Right 1	Reference ≤2.00 mm/m	│TV-Ref│≤0.35 mm/m
IRI Right 1	Reference >2.00 mm/m	│TV-Ref│≤0.35+(Ref-2.00)×10%) mm/m
Rut Depth 3.2 m, Sliding Wire Rut Depth 1	Reference ≤7.5 mm	│TV-Ref│≤1.0 mm
Rut Depth 3.2 m, Sliding Wire Rut Depth 1	Reference >7.5 mm	│TV-Ref│≤1.0+(Ref-7.5)×5% mm
Position, coordinates lat, long[7] 1		│TV-Ref│≤ 1 m
Position, MAMSL 1		│TV-Ref│≤ 1 m
Crossfall 1	│Reference│ ≤ 3.00%	│TV-Ref│≤ 0.50 %
Crossfall 1	│Reference│ > 3.00%	│TV-Ref│≤ (0.50+(│Ref│-3.0)×5%) %
Hilliness 1	│Reference│ ≤ 3.00%	│TV-Ref│≤ 0.75 %

[7] Modified from the Swedish requirements.

Variable	Category	Acceptance interval
Hilliness 1	│Reference│ > 3.00%	│TV-Ref│≤ (0.75+(│Ref│-3.0)×5%) %
Transverse profile (middle 2 m) 1		Point by point │TV-Ref│≤ 0.5 mm
MPD right 1	Reference ≤ 1,2 mm	│TV-Ref│ ≤ 0,10 mm
MPD right 1	Reference > 1,2 mm	│TV-Ref│ ≤ (0,10+(Ref-1,20) x 10%) mm
Megatexture right 1	Reference ≤ 0,3 mm	│TV-Ref│ ≤ 0,10 mm
Megatexture right 1	Reference > 0,3 mm	│TV-Ref│ ≤ (0,10+(Ref-0,30) x 5%) mm
Longitudinal profile, correlation[8] 1		≥0.8
Longitudinal profile, standard deviation quota[3] 1		≥0.8
Cracks[9] 1		TV-Ref ≤ 2.5 %

Additional threshold levels

Table 53 Additional threshold levels for the validity test.

Variable	Category	Acceptance interval
IRI Right 2	Reference ≤ 2.00 mm/m	│TV-Ref│≤0.5 mm/m
IRI Right 2	Reference > 2.00 mm/m	│TV-Ref│≤0.5+(Ref-2.00)×20%) mm/m
Rut Depth 3.2 m 2 Sliding Wire Rut Depth 2	Reference ≤ 7.5 mm	│TV-Ref│≤2.0 mm

[8] Method described in chapter 7.1.3.

[9] Slightly modified from the Swedish requirements.

Variable	Category	Acceptance interval
Rut Depth 3.2 m 2 Sliding Wire Rut Depth 2	Reference > 7.5 mm	│TV-Ref│≤2.0+(Ref-7.5)×15% mm
Position coordinates lat. long. 2		│TV-Ref│≤ 5 m
Height MAMSL 2		│TV-Ref│≤ 5 m
Crossfall 2	│Reference│ ≤ 3.00%	│TV-Ref│≤ 0.75 %
Crossfall 2	│Reference│ > 3.00%	│TV-Ref│≤ (0.75+(│Ref│-3.0)×10%) %
Hilliness 2	│Reference│ ≤ 3.00%	│TV-Ref│≤ 1.0 %
Hilliness 2	│Reference│ > 3.00%	│TV-Ref│≤ (1.0+(│Ref│-3.0)×10%) %
Transverse profile (middle 2 m) 2		Point by point │TV-Ref│≤ 1 mm
MPD right 2	Reference ≤ 1.2 mm	│TV-Ref│ ≤ 0.20 mm
MPD right 2	Reference > 1.2 mm	│TV-Ref│ ≤ (0.20+(Ref-1.20) x 20%) mm
Megatexture right 2	Reference ≤ 0.3 mm	│TV-Ref│ ≤ 0.15 mm
Megatexture right 2	Reference > 0.3 mm	│TV-Ref│ ≤ (0.15+(Ref-0.30) x 10%) mm
Longitudinal profile. correlation 2		≥ 0.9
Longitudinal profile. standard deviation quota 2		≥ 0.9
Cracks 2		TV-Ref ≤ 1 %
WLP σ_{WLP} 1	Reference ≤ 5.40 mm	│TV-Ref│ ≤ 0.9 mm

Variable	Category	Acceptance interval
WLP σ_{WLP} 1	Reference > 5.40 mm	│TV-Ref│ ≤ 0.9+(Ref-5.40)×10%) mm
WLP Δ_{WLP} 1	Reference ≤ 27.0 mm	│TV-Ref│ ≤ 4.4 mm
WLP Δ_{WLP} 1	Reference > 27.0 mm	│TV-Ref│ ≤ 4.4+(Ref-27.0)×10%) mm
WLP σ_{WLP} 2	Reference ≤ 5.40 mm	│TV-Ref│ ≤ 1.3 mm
WLP σ_{WLP} 2	Reference > 5.40 mm	│TV-Ref│ ≤ 1.3+(Ref-5.40)×20%) mm
WLP Δ_{WLPM} 2	Reference ≤ 27.0 mm	│TV-Ref│ ≤ 6.3 mm
WLP Δ_{WLPM} 2	Reference > 27.0 mm	│TV-Ref│ ≤ 6.3+(Ref-27.0)×20%) mm
Lane width 1		│TV-Ref│≤ 20 mm
Lane width 2		│TV-Ref│≤ 50 mm
Object position 1		│TV-Ref│≤ 50 mm
Object position 2		│TV-Ref│≤ 100 mm
Object height 1		│TV-Ref│≤ 50 mm
Object height 2		│TV-Ref│≤ 100 mm
Wide transverse profile height 1		│TV-Ref│≤ 2 mm
Wide transverse profile height 2		│TV-Ref│≤ 5 mm

Repeatability

Standard threshold levels

This chapter describes threshold values used in Sweden and in this test.

Table 54 Standard threshold levels for the repeatability test.

Variable	**Percentile 75 %**
IRI right 1	≤ 0.20 mm/m
Rut Depth 3.2 m 1 Sliding Wire Rut Depth 2.0 m 1	≤ 0.5 mm
Crossfall 1	≤ 0.20 %
Hilliness 1	≤ 0.20 %
MPD right 1	≤ 0.10 mm
Megatexture right 1	≤ 0.10 mm
Longitudinal profile right[10] 1	≥ 0.8

Speed dependency

Standard threshold levels

This chapter describes threshold values used in Finland and in this test.

Table 55 Standard threshold levels for the speed dependency test.

Variable	**Difference**
IRI right 1	≤ 0.10 mm/m
Rut depth 3.2 m 1 Sliding wire rut depth 2.0 m 1	≤ 0.2 mm
Crossfall 1	≤ 0.15 %
Hilliness 1	≤ 0.20 %
MPD right 1	≤ 0.05 mm
Megatexture right 1	≤ 0.025 mm
Position 1	≤ 0.5 m

[10] Tested with the routine described in chapter 7.2.1.

Additional thresholds

The threshold values in this chapter are experimental. In some cases. there is no or little experience of testing the variables. Some variables are repeated in this chapter. This indicates the second level of threshold to be tested.

Table 56 Additional threshold levels for the speed dependency test.

Variable	**Difference**
IRI right 2	≤ 0.40 mm/m
Rut depth 3.2 m 2 Sliding wire rut depth 2.0 m 2	≤ 1.0 mm
Crossfall 2	≤ 0.40 %
Hilliness 2	≤ 0.40 %
MPD right 2	≤ 0.20 mm
Megatexture right 2	≤ 0.15 mm
Longitudinal profile. correlation 2	≥ 0.9
Longitudinal profile. standard deviation quota 2	≥ 0.9
WLP σ_{WLPL} 1	≤ 0.3 mm
WLP Δ_{WLPL} 1	≤ 1.6 mm
WLP σ_{WLPL} 2	≤ 0.4 mm
WLP Δ_{WLPL} 2	≤ 2.3 mm
Position 2	≤ 1 m
Lane width 1	≤ 10 mm
Lane width 2	≤ 25 mm
Object position 1	≤ 25 mm
Object position 2	≤ 50 mm
Object height 1	≤ 25 mm
Object height 2	≤ 50 mm

Annex 2. Detailed results for the participants

PDFs with individual participant results are available in a zip file, which can be downloaded from this reports post in the DIVA portal. The files are sorted by participant code; for example, System B has five documents.

System_B_Longitudinal_profiles_REF.pdf describing validity of longitudinal profiles

System_B_Longitudinal_profiles_UH.pdf describing repeatability of longitudinal profiles

System_B_Repeatability.pdf describing repeatability of delivered 20 m variables

System_B_Validity_REF.pdf describing validity of delivered 20 m variables, using dedicated reference measurements as reference

System_B_Validity_SUP.pdf describing validity of delivered 20 m variables, using system average as reference

The number of PDF documents provided depends on the specific variables delivered.

System A

Three documents

System B

Five documents

System D

Five documents

System E

Five documents

System H

Three documents

System I

Three documents

System J

Five documents

System K

Five documents

System L

Five documents

System M

Five documents

System N
Five documents

System O
Five documents

System P
Five documents

System Q
Three documents

System R
Five documents

System S
Five documents

System T
Three documents

System U
Five documents

System V
No documents

System W
Three documents

System X
Five documents

System Y
Five documents

System Z
Five documents

Annex 3. System descriptions

This annex describes the participating systems. The text has been written by the participants and is not further reviewed.

Ramboll Sweden AB

The Ramboll RST Survey System is an advanced contact-less measurement system for surveying road surface characteristics and road area scanning. All Ramboll RST systems have a modular architecture with the same core synchronization unit. Depending on what capabilities a system should have modules, sensors and functionality can be easily added. Modules and sensors can be connected via several different interfaces such as ethernet, USB, CANBUS and serial interfaces.

The system used in duraBASt was equipped with high resolution point lasers, accelerometers, a 3D imaging sensor system, an INS with IMU, a DMI and Right-Of-Way camera for measurement of the road surface characteristics. It was also equipped with LiDAR scanners and 360 camera system for road area scanning.

The measurement system meets and fulfills the requirements and standards declared by the Swedish National Road Administration (SNRA) for road surface measurement.

The system can measure the road surface longitudinal and transverse profile with mm resolution. From the longitudinal profile various longitudinal unevenness parameters can be calculated such as IRI, RMS for various wavelength categories, elevation profile, relative slope profile and a variety of Comfort values all in accordance with ASTM E1926, ASTM E950 and other national standards.

The system measures and provides road surface texture parameters such as MPD, RMS texture (Mega, Macro, Micro) and others in accordance with ISO-13473 and EN13036 (Class 1 equipment).

From the transverse profile various transversal parameters can be calculated such as rut depth, water depth, edge drop off and more in accordance with various ASTM and AASHTO, for example ASTM E1703. The base transversal profile width is up to four meters, but extended transverse profiles with larger width can be calculated.

Road geometry parameters such as crossfall, hilliness and curvature can be calculated. The high accuracy INS can provide cm level (RTK) location accuracy.

The 3D Imaging system can provide road surface images with 1x1 mm resolution, and automated crack and defect detection and analysis can be performed.

Point clouds and shape files with geo-tagged data can be generated for the road surface parameters.

For road area scanning the survey grade LiDAR scanners and the 360 spherical 100% FOV camera system can provide high resolution correctly colorized point clouds. With the RTK level location of the point cloud a high accuracy digital twin of road surface and road area can be created.

Feature detection can be performed to create inventory and position of various objects, but also to detect for example faces, number plates and such so they can be blurred for GDPR compliance.

VTI

VTI Mobile Research Platform is a flexible and future-proof measurement system used to describe the condition of the road surface and the road surrounding. The measurement is carried out at traffic speed without affecting the variables. The measurements meet the Swedish Transport Administration's standards and requirements.

The properties that can be measured are divided into the condition of the road surface and the road surroundings.

Road surface condition

The measurement is done in a non-contact way by so-called non-destructive laser measurement. A high-resolution line laser is used to collect a continuous cross profile with sub-millimeter resolution. The longitudinal profile is collected with a spot laser. It describes the roughness of the road in wavelength ranges up to 100 meters. Positioning of the measurement is done with GNSS-INS (Global Navigation Satellite System-Inertial Navigation System) and traveled distance, which means that data can be positioned with centimeter accuracy.

The data collected on road surface condition:

- Longitudinal profile: to assess irregularities in the longitudinal direction of the road.
- Transverse profile: Up to 4 meters wide with a grid of 1×1 mm. Used to assess wear and deformation.
- Cross slope: To assess water run-off.
- Curvature: Describes road geometry.
- Hilliness: Describes road geometry.
- Megatexture: Describes short irregularities.
- Macrotexture: Describes the surface texture, important for durability, fuel consumption, safety and noise.
- Cracks and surface defects: To assess the durability of the road.
- Temperature (air and road surface), fuel consumption, noise (environmental variables).
- Open channels dedicated to optional measurement sensors that can be used for research and development.
- Pictures: For documentation and verification

We have software to calculate the standardized variables described in EN 13036- and ISO 13473-series.

The mobile mapping survey uses the latest technology, with two Lidar scanners imaging the road surface and the surrounding, up to 100 m at each side of the road. This is combined with a 360 camera to create a digital twin (3D model) of both the road surface and the road surrounding – all linked to a coordinate system.

The digital twin describes the terrain around the road within 100 meters and can be used to detect and position objects such as signs, traffic lights and crash barriers.

Université Gustave Eiffel

UniBox

UniBox is a compact, easy-to-use and budget-friendly profilometer for measuring longitudinal irregularities with wavelengths ranging from 0.5m to 50m. It is composed of one or two measurement boxes with laser point (to cover right and left wheel paths simultaneously) and a data acquisition box that also ensures the power supply. The system required a GPS receiver for computing the curvilinear abscissa and geolocation; it can be completed with a wheel encoder and a camera. UniBox is able to perform at traffic speed and is particularly adapted to the following applications:

- Monitoring of the road networks (fits well for the case of secondary roads);
- Controlling the evenness of the pavement layers (surface, base course, sub-base course) during construction or maintenance works (many users are works companies to control themselves during the process);
- Controlling the longitudinal profile for specific infrastructure (e.g. special lane for bus, trolleybus, etc.).

UniBox runs with proprietary software for the data acquisition and analysis. The road profile signal and the corresponding indicators (IRI & French indicator NBO) can be easily and quickly processed for in situ operations.

UniBox is a certified measurement system (mlpc®) commercialized since 2015. It is used in France by over fifty companies and administrations, as well as worldwide (Africa, Asia and South America).

UniBox (L-Type) with 1-path configuration

UniBox (N-Type) with 2-paths configuration

Miranda

MIRANDA is an end-to-end solution for monitoring ride comfort on networks “anywhere” and at “any time” by using smartphone as both sensor and data logger. MIRANDA has been designed to be used by a large number of probe vehicles and therefore to provide numerous surveys. This offers fast coverage of the entire road network on one hand and strengthens the quality of the indicator by taking advantage of the repeatability of measurement on the other.

As the data collected by MIRANDA corresponds solely to the movements of the car body (without being able to differentiate between left and right wheel paths), it is able to provide a “mean” road profile signal that includes longitudinal irregularities with wavelengths ranging from approximately 3m to 50m. This range includes therefore the deformations that cause comfort issues and allows the calculation of an IRI estimate.

MIRANDA is a process which starts with the use of an Android application on the smartphone to collect the raw data. This application, developed by UGE, is able to send the measurement file to a server via a wireless connexion in order to be processed automatically (map matching, calculation of the profile and the corresponding indicator). The information is then entered into a database from which the road manager can run various types of queries (data fusion, setting thresholds, visualizing the result with a GIS, extracting the result over a period, exporting to CSV file, etc.).

MIRANDA has been tested by several managers in France during large-scale (thousands of kilometers) and long-term experiments (1 to 3 years) in real conditions. Most of them have used the results to maintain the level of service on rural roads and control the quality of works over a long period. MIRANDA is also used in other European and African countries for research activities.

Illustration of MIRANDA with screenshots of the Android application and a map of road indicators in La Manche department (France) during a large-scale experiment

UniWheel

UniWheel is an equipment based on a non-optical sensor mounted near the rear wheel support of a vehicle. It is able to provide a road profile signal that includes longitudinal irregularities with wavelengths ranging from approximately 2m to 50m. In this way, traditional road indicator such as the IRI can be estimated with a good level of confidence although it is more or less sensitive to the nature of the vehicle and its condition. The equipment is completed with a specific data logger that can manage 1 or 2 sensors simultaneously (to provide measurements in the right and left wheel paths) as well as a GPS receiver for calculating the curvilinear abscissa and the geolocation. The acquisition process can be controlled remotely from a smartphone or PC through a wireless connection to the data logger. This equipment has been designed in order to be embedded in a fleet of professional vehicles (typically belonging to road managers) in order to monitor the network regularly on all types of roads and in all weathers.

UniWheel sensor and other components

AIT — RoadLab

FLEXIBLE MONITORING OF ROAD SURFACES AND ROAD CORRIDOR FOR SUSTAINABLE ASSET MANAGEMENT

The high-performance measuring vehicle RoadLab is equipped with state-of-the-art sensors, satellite navigation and camera technology. It records the most important properties of the road surface and road environment with the highest quality and accuracy and can even be used on cycle paths and side roads thanks to its compact design. Thanks to its variable design concept, it is easy to integrate a wide range of sensor technologies, which subsequently enable AI-supported data evaluation and assessment.

MODULAR EQUIPMENT	POTENTIAL APPLICATIONS
• Highest precision in the detection of road geometry and localization of road objects thanks to the Applanix positioning system • Dead reckoning for uninterrupted positioning even in the event of satellite shadowing • 4K video systems • 360° panoramic camera • Laser scanner for capturing the road corridor • Laser scanner for capturing the road surface • Flexible platform for sensor integration	• Recording and evaluation of cycle paths • Condition assessment of municipal road networks (surface distress, rutting, longitudinal evenness) • AI-supported evaluation of surface distress • Video documentation with 360° camera and 4K camera systems • Determination of alignment parameters (gradient and crossfall, curve radius) • Inventory of traffic signs, road markings, etc. • Checking the clearance profile • Determination of lane widths • Detailed 3D roadway models in OpenCRG and FBX

The high-precision recording of the road condition and, if necessary, the road environment provides infrastructure operators with an important decision-making basis for sustainable and cost-efficient maintenance planning and an increase in road safety. The measurements are carried out without interfering with moving traffic.

Figure 76 AIT RoadLab.

CV Equipment Vectra (NextRoad group)

NextRoad is an independent, French company specializing in the diagnosis, expertise, and inspection of road infrastructures. We operate during the construction and operational phases, providing services and technologies aimed at increasing the sustainability of these infrastructures. Under the VECTRA brand, the company designs and manufactures a wide range of inspection vehicles for assessing pavement condition (macrotexture, cracking), structural integrity for roads and subgrades (deflection, bearing capacity), road profiles (laser or mechanical), road markings visibility (mobile retroreflectometer), and pavement friction (roads and runways).

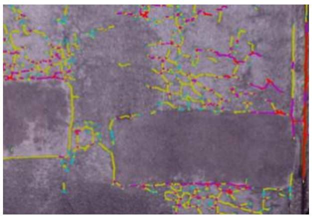
Vectra NextRoad Engagé pour des infrastructures durables

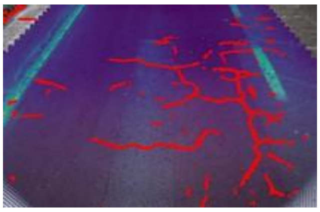
XenomatiX

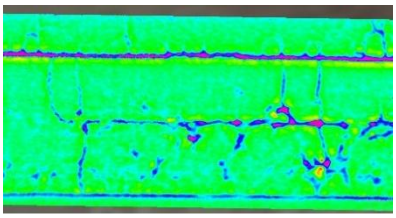
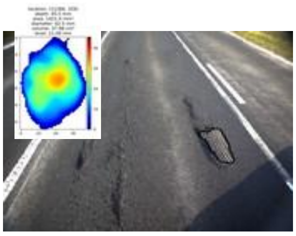
6D Road Scanning

XenomatiX offers a versatile solution suitable for any pavement type and size, helping plan road repairs in a timely manner. Pavement inspectors, contractors, surveyors and road network managers turn to XenomatiX for applications like:

1. Pavement condition monitoring
2. Quality control of new roads
3. Road markings checks
4. Crack, pothole, patch, manhole, detection
5. Bike lane inspections
6. Sidewalk assessments

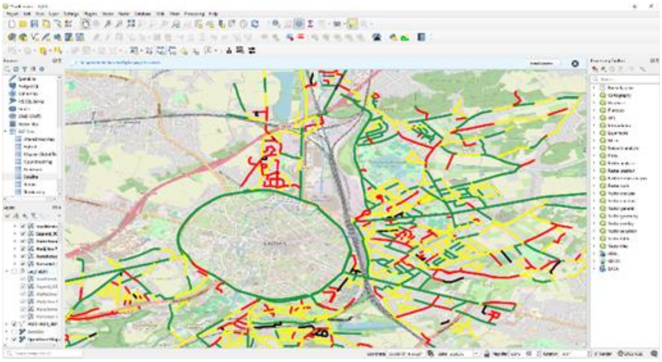




How it works?

XenoTrack measures pavement **crack and pothole** density and severity, along with indices like **IRI, MPD, PCI and rutting**. The data is geo-tagged and exported in any **GIS system**. By color-coding the GIS layer in function of the pavement quality indices, the heightmap locates areas that require attention. The local height of the road surface illustrates any deformation or distress of the road and **provides valuable insights into cause** and **necessary pavement repairs**. Measurements are done up to 90km/h at the highest performance, including uninterrupted start&stop.



BASt Benchmark:

XenomatiX participated in the category of Mobile Mapping systems for Validity and Repeatability in 9 out of the 11 benchmarks. Contact XenomatiX to obtain the letter code.

Roadscanners

Intelligent and Proactive
Infrastructure
Asset management

The Road Doctor® Survey Van represents a new era in road survey technology. This state-of-the-art vehicle, following a design philosophy of sensor-fusion, incorporates advanced technologies, namely GPR, LiDAR and 3D Accelerometer, into a user-friendly package. By integrating the unique and innovative Road Doctor® survey packages into a single system, the RDSV sets a new standard for road assessment.

The technologies selected for the RDSV ensure accurate and comprehensive surveys, enabling proactive maintenance strategies to extend pavement lifetime and improve usability of transportation infrastructure. Some infrastructure related applications of ground penetrating radar (GPR) include detection of structures, layer thicknesses, moisture, and road construction quality control. LiDAR can be used to measure rutting, crossfall, ditch depths, road widths and surroundings (point cloud). 3D Accelerometer measures pavement roughness (IRI class 3) along with wavelength-based roughness analysis. It is also possible to add an additional device to obtain IRI class 1 results.

With videoing system you can conduct pavement distress, road furniture, and drainage inventories by defining up to 10 parameters across 4 classifications, utilizing continuous inputs (e.g. drainage, cracking) or point-like designations (e.g. culverts). Generate outputs at customizable intervals (e.g. 10 m, 100 m) and conveniently perform inventory tasks in the field or at the office using high-definition video.

Alongside the emergence of smart cities and intelligent transportation systems, the RDSV can play a key role in the next generation of intelligent asset management. By providing comprehensive data on road condition, the system empowers decision-makers to optimize maintenance schedules, allocate resources efficiently, and prioritize repairs based on accurate up-to-date assessments. This proactive approach not only improves road safety but also enhances the overall efficiency of transportation networks.

Nordic GeoCenter

The RIEGL VMX-2HA is a high-speed, high-performance dual scanner mobile mapping system designed to deliver dense, accurate, and feature-rich data while operating at highway speeds. With up to 3.6 million measurements per second and 500 scan lines per second, it provides survey-grade mobile mapping ideal for a wide range of applications including transportation infrastructure assessment, road surface analysis, city modeling, and more. With support for up to 9 optional cameras, the system captures precise geo-referenced imagery that complements the LiDAR data and enriches project details.

The system's versatility is amplified by a selection of up to nine different cameras—from high-resolution spherical cameras up to 72 MP to specialized RIEGL cameras with minimal lens distortion (5MP, 12MP, 24MP)—allowing tailored camera setups for specific project needs. At its core, the VMX-2HA integrates two RIEGL VUX-1HA22 high-accuracy LiDAR sensors paired with a high-performance INS/GNSS unit, all protected within an aerodynamically optimized housing. The lasers operate safely under Laser Class 1 regulations. Optional systems, such as the Pavement Camera System, enable high-resolution image capture of the road surface.

RIEGL's comprehensive software suite supports a smooth workflow, guiding users seamlessly from mobile laser scanning (MLS) through data processing and adjustment to final deliverables.

Using the VMX-2HA, road owners and engineers can survey entire roadway areas with exceptional accuracy thanks to RIEGL's proprietary SMART waveform analysis technology. Its extended range (up to 475 meters) enables reliable scanning of complex environments—including challenging multi-layered structures and dark surfaces—ensuring complete and detailed data capture. The resulting point cloud combines high positional accuracy with rich additional attributes that simplify downstream processing and modeling. For example, the reflectance value (distance-calibrated intensity) provides stable, consistent RGB-like information even in the absence of camera data.

The VMX-2HA is built to support the full lifecycle of road infrastructure projects—from initial design and construction through ongoing monitoring and maintenance. It is also possible to extract essential road surface parameters such as the International Roughness Index (IRI) directly from laser scan data. Importantly, the system delivers precise measurements of both horizontal and vertical road geometry, empowering road owners and engineers with accurate, actionable data to improve safety, and maintenance planning.

Leica Geosystems

Leica Pegasus TRK700 Evo

The Leica Pegasus TRK700 Evo is a high-precision mobile mapping system suitable for a wide range of applications, including road and infrastructure projects requiring rich, georeferenced datasets for surface documentation, asset inventory, and condition monitoring. For the duraBASt test, the system was configured with pavement-facing cameras to enable detailed visual capture of surface textures and damage patterns relevant to pavement assessment.

At the core of the Pegasus TRK700 Evo is a dual-laser scanner capable of collecting up to 4.4 million points per second. The dual laser scanners generate dense, high-precision point clouds, while the pavement cameras and the integrated 360° panoramic camera capture detailed visual context in parallel, all in a single pass. This enables engineering-grade modelling of road surfaces, supports wear and damage detection, and captures full spatial context even at traffic speeds. Integrated IMU and SLAM ensure positioning reliability in tunnels, underpasses, or built-up areas where GNSS signals may be obstructed. The rotating-tilt mount simplifies single-person installation and allows flexible scanner positioning for more efficient operation.

The system's software workflow is designed to minimise turnaround time and reduce manual overhead. Pegasus FIELD, a browser-based interface, is used to capture data in the field. It allows operators to plan missions and monitor data collection during capture. RTK support enables in-field data export where required, while GDPR-compliant anonymisation is handled automatically during acquisition. Captured data can be seamlessly processed in Pegasus OFFICE, which provides tools for trajectory refinement, point cloud classification, and export to BIM, CAD, or GIS-compatible formats. This smooth transition from field to office ensures that high-quality results are delivered efficiently and consistently.

Thanks to modular add-ons, the Pegasus TRK700 Evo can be tailored to different project needs. Users can extend the system with additional cameras, including side, rear, or butterfly configurations, and integrate mechanical or optical distance measurement instruments as required. This modular approach makes it easy to adapt the system to diverse road environments, such as rural networks, urban streets, or complex intersections, and to align data capture with specific survey goals like texture analysis, surface profiling, or asset inventory.

The Pegasus TRK700 Evo is part of the wider Pegasus TRK portfolio, offering users a scalable path based on project requirements. For more compact deployments, the Pegasus TRK300 provides a lightweight alternative at just 14 kg. For extended range applications, the Pegasus TRK Neo models deliver the longest scanning distances in the series. A clear upgrade path allows teams to scale capabilities over time, ensuring long-term value and flexibility for organisations investing in mobile mapping.

Mercedes Benz

Measuring Waviness with the Mercedes-Benz Customer Fleet

Modern premium vehicles with advanced driver assistance systems are equipped with a multitude of sensors, like radar, mono and stereo cameras, ultra sonic, potentially lidar and also more traditional sensors like wheel speed sensors or acceleration sensors to monitor the driving state with a high resolution. For our waviness product we rely on the vehicle level sensor that continuously measures the offset of each of the wheels regarding the chassis. This sensor is widespread in Mecedes-Benz production cars with their advanced suspension systems.

The vehicle level sensor signal captures a mixture of influences: Of course it contains the waves of the road we are looking for. At the same time, it also contains the relatively low oscillation of the vehicle chassis itself and the comparably high vibrations of the wheels. Based on the known natural frequencies of both we can separate the road waviness with sufficient accuracy from the vehicle and tire excitations. The part of the frequency spectrum describing the actual road highly depends on the speed of the car. Fortunately, in practice that is not an issue at all. How to come to proper results is described in detail in [Hipp 2011, Hipp 2023], see below.

Concerning our measurement setup, the usage of the vehicle level sensor is crucial. It directly measures at least part of the actual vertical road profile. Other sensors try to measure this indirectly, for example wheel speed sensors may be employed in such a way. In our experiments such indirect measurements were far off and at the same time we had to deal with a huge overhead in method implementation and actual analysis. In our experience to analyze the wheel levels is the straight forward and natural way to go if you want to reliably derive road waviness from a fleet of production vehicles.

At the same time modern cars are always online, meaning they are fully connected to a backend and can exchange information with its OEM, if customer consent is granted. In our case this is the Mercedes-Benz Intelligent Cloud within the Mercedes-Benz Operating System (MB.OS).

Not using a single vehicle as a separate measurement unit but considering the whole customer fleet as one ubiquitous sensor makes our approach gain its full momentum. From the billions of miles driven by our customer cars we aggregate or waviness values. This means:

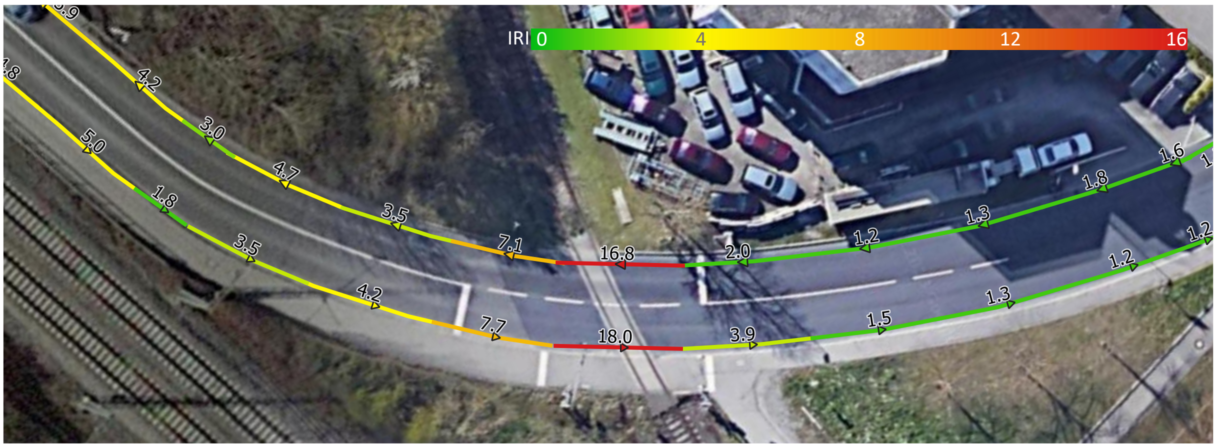
- No special hardware, no dedicated measurement campaigns or measurement vehicles
- Realtime: waviness immediately available as soon as the first Mercedes-Benz passes a road, technically no matter where in the world this is.
- We deliver IRI and RMS, other measures are to come (AUN according to ISO8608 is fully tested)
- Our figures are of adequate quality and supplement conventional ground truth data from dedicated measurement vehicles

In the future we will improve our system further as modern chassis components offer acceleration sensors that go far beyond simply measuring the vehicle level.

References:

J. Hipp, M. Haueis, R. Dörr, J. Rauh: Method for classification of surface profile, Patent DE102011120022A1, Daimler AG, 2011

J. Hipp, K. Massow, R. Grote, J. Pontow, S. Züfle, T. Espenschied, M. Haueis, P. Blume, I. Radusch, M. Bontenbal: Vehicle Fleet Data for Cost Efficient Real-Time Road Surface Assessment, In: The IAVSD International Symposium on Dynamics of Vehicles on Roads and Tracks, pages 549-561, Ottawa, Canada, Springer, 2023



Vehicle derived IRI-10 at railroad crossing in Böblingen (Germany). Images ©2023 Google, GeoBasis-DE/BKG (cited from Hipp 2023)

ARRB Systems

ARRB Systems participated the "Test of road monitoring equipment's at duraBASt 2024" with its Roughometer 4 measurement system. The system was developed for providing simple, portable and highly repeatable measurements of road roughness, on sealed and unsealed roads.

The Roughometer 4 is a World Bank Class 3 response-type device, measuring IRI directly from the axle movement using a precision accelerometer. This eliminates the uncertainties typically associated with other roughness response type meters or phone applications, such as the vehicle's suspension, or varying fuel and passenger weights. The unit utilizes a wireless distance sensor and can be operated with most Android phones or tablets. Survey data is stored on the Android device, with the amount of collected data only limited by the storage capacity of that device.

The system is compliant with international standards, like World Bank Technical Paper #46, ASTM E1926, ASTM E1082, ASTM E2560, EN 13036-5, EN 13036-6, TMH 13 Part C and IRC:SP:16.

The Roughometer 4 system contains the following components:

- accelerometer and mounting hardware
- interface module
- USB charger (for 12 V or 24 V vehicles)
- data cable (8 m long)
- accelerometer mount installation cable (0.4m long, curly)
- wireless buttons:
  - Reference button
  - Event button
- OBDII (OBDLink) wireless speed transmitter

The system is operated by using two wireless buttons mounted on the vehicle dashboard. The wireless distance sensor eliminates the need for wheel mounted devices. Optional externally mounted Distance Measurement Instrument (DMI) available, which was used at the duraBASt 2024 test.

The unit also allows for MP3 voice recording of events.

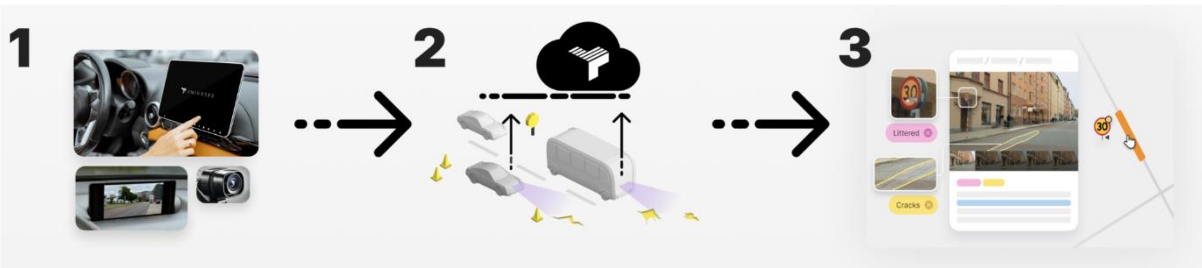
The Roughometer 4 utilizes GPS functionality of Android device, with collected surveys displayed on a Google Maps interface.

For data evaluation multi-format reports available including KML and CSV files.

Univrses

3DAI™

Univrses' 3DAI™ solution is a data collection and distribution platform built to harness large volumes of real-time data from connected vehicles in order to streamline road management operations. The system leverages cameras, and other sensors, integrated into vehicles already operating on the roads (e.g. taxis, waste management vehicles, municipal vehicles, and OEM customer fleets) as well as external data sources. The images and other data are processed in the vehicle (at the "edge") using Univrses' proprietary perception software.



Data is collected from multiple vehicles already on the road	Data is automatically merged and transformed into insights about road infrastructure	Data is accessed via API or a user-friendly format in our interactive web app

3DAI™ provides a cost-effective, scalable solution to continuously assess infrastructure, ensuring safer, cleaner, and more accessible transport routes. The system provides accurate, up-to-date insights, reducing manual inspections and ensuring a more efficient, data-driven approach to road and transportation management. By replacing manual inspections with AI monitoring, road owners and others can prioritize and predict maintenance needs to reduce costs and optimize budgets. 3DAI™ can detect and classify multiple objects from the road environment, for example traffic signs, road works, streetlights and road damage, described in more detail below.

3DAI™ is capable of detecting road damage and providing estimates of the road surface deterioration, including multiple road surface features. Univrses has spent years developing computer vision and sensor processing algorithms for detecting road damage in different territories.

3DAI™ data includes detailed information about the shape, position and size of detected surface damages, delivered on a daily basis. Data that is regularly updated, accurate and reliable enables a proactive management model. The data in 3DAI™ is aggregated together if vehicles collect multiple times on the same road; each instance (e.g. pothole, crack, patch, etc.) is tracked over time making it possible to detect changes. This makes it possible to improve life-cycle predictions about road assets; this enables the user to plan corrective repairs or treatments at the right time, thereby increasing safety and reducing costs.

CV Equipment Vectra (NextRoad group)

NextRoad is an independent, French company specializing in the diagnosis, expertise, and inspection of road infrastructures. We operate during the construction and operational phases, providing services and technologies aimed at increasing the sustainability of these infrastructures. Under the VECTRA brand, the company designs, manufactures, and distributes worldwide an extensive range of road and runway inspection vehicles for assessing pavement condition (LCMS), deflection, bearing capacity, geometry, road markings visibility, and pavement friction.

Danish Road Directorate

Vejdirektoratets ARAN

The Danish Road Directorate purchased an ARAN from Fugro in 2018 and put into the production of data in 2019.

The vehicle carries the Pavemetrics LCMS 2 system and 2 SELCOM point lasers. Besides IMU, Odometer, Gyro, GPS etc.

From the ARAN we record IRI, MPD and rutting (by the Straight Edge method). We’ve used the crack detection from VISION as a part of our maintenance plan.
We’ve also used the surface images to train AI models to find, and identify, road markings, along with other assets.

Images from the ROW camera have also been used in the DRD’s “road in images” database.

System	Frequency	Resolution	Range	Output
LCMS2	28 kHz	2 x 1 mm (longitudinal x transverse)	4.2 m 7296 pixels	Pavement scan
Point lasers	62 kHz	<1mm, speed dependent	In wheel paths ~0-60mm over road	IRI and MPD

VARS

CleveRA Car is a unique measuring vehicle from VARS BRNO, built on a Mercedes-Benz Sprinter platform and designed for mobile road diagnostics during normal traffic. The vehicle is fully approved for use on public roads in the Czech Republic and represents a cutting-edge technical solution for the Road Management System (SHV).

The dominant feature of the vehicle is a roof-mounted ramp with front and rear cameras and LCMS-1 sensors, which enable the scanning of a 4 m wide strip of road surface at speeds of up to 80 km/h with a resolution of 1 mm and a height accuracy of 0.5 mm. Precise positioning is achieved by the POS LV 220 system GNSS/INS from Applanix. The system uses IMU, dual GNSS antennas, and Kalman filtering for data integration. Distance measurement accuracy is 0.04%, speed accuracy is 0.1 km/h.

Longitudinal profile is captured by laser sensors with 0.01 mm vertical resolution and 32 kHz sampling. Macrotexture is measured by three lasers with 0.01 mm resolution and 64 kHz sampling; MPD is calculated according to EN ISO 13473-1.

Transverse profile and rut depth are captured by the LCMS system, creating a 3D image of the surface up to 4 m wide. Resolution is 0.5 mm, with 4096 profile points. Rut and water depth are calculated during post-processing.

Surface defects are documented using LCMS and a camera system. LCMS captures orthophoto images (4×10 m), while cameras record Full HD images every 5 m. Images are independent of lighting and include positional data.

This allows real-time collection of data on the current condition of the road, which is then used for maintenance and repair planning. As a result, the service life of roads can be effectively extended and the costs of their management optimized.

Inside the vehicle are server cabinets, powerful UPS batteries, and specialized electronics that ensure the operation of the measurement systems and immediate data storage. All components were integrated by the Swedish company Ramboll, a specialist in diagnostic vehicles.

The vehicle's crew consists of a driver and an operator who monitors and validates the measurement process.

CleveRA Car is the only vehicle of its kind in the Czech Republic that enables comprehensive road diagnostics in a single pass. Its outputs serve as a basis for managers.

Geodrom

GEODROM – Trimble MX9

Our company Geodrom used our mobile mapping system Trimble MX9 for the test of road monitoring at duraBASt test site on 15th October 2024. Mobile mapping system is mounted on the car roof by special rack. The measuring unit is contained of panoramic camera Ladybug 5+, inertial unit (IMU), GNSS antenna and pair of lasers scanners. Other components are secondary GNSS antenna for better calculations of heading orientation, computer case for storing measured data and some other devices securing power supply for the system.

During the measurement mobile mapping system is receiving GNSS data and calculating approximate position with together with the data of IMU, which is calibrated at the start of mapping mission. Mobile mapping system also collects 32 MPx panoramic photographs. Crucial for the test are point cloud measured by the pair of Riegel laser scanners. They are 360° (full circle) type of scanner, which collect point cloud data with frequency 250 Hz. This means that every second scanners make 250 full 360° scan behind the car. Laser scan also beam signal with frequency 500 kHz which measure 1 point.

Data are post-processed with rinex data measured during the mobile mapping system measurement mission on the point with know coordinated. The usage of rinex correction data make trajectory of mobile mapping system more accurate (error in centimeters). The accurate trajectory can be transformed into required coordinate system. The accurate trajectory is used for point clouds generation by GPG time stamps. The points contain coordinates and information about intensity of surface. The point cloud representing whole surface of the scanned road and surrounding objects.

The resulting cloud in the right coordinate system can used for any calculations of indices of road quality on the specific required line, which is defined in the same coordinated system. We can also make sections in any position.

Norwegian Public Roads Administration

The Norwegian Public Roads Administration has about 5000 colleagues divided into six divisions and a Road Directorate.

Participants are organized under the Norwegian Public Roads Administration in the Section for Geomatics Operation and Maintenance. The main task for the test car/equipment is registration of pavement condition on E/Rv in Norway.

The system with laser and positioning equipment has been in operation since 2015, the IRI meter is from 2022, and the camera system from 2019 (2-camera setup mounted behind the windscreen).

Laser scanner is Z+F Profiler 9012

Positioning equipment is Applanix POS LV 220 with IMU-42

Camera System er acA24440-20ge

IRI is "ViaIRI kHz70"

GRID

Leica Pegasus TRK700 Evo – Technical Specification

Identification of the Measuring Device:

Name/Type: Leica Pegasus TRK700 Evo

Serial No.: 297205

Manufacturer: Leica Geosystems AG, Widnau, Switzerland

Laser Scanners:

Two 2D Z+F PROFILER 9020 scanners with angled scanning planes.

- Max profile rate: 534 profiles/s (267 per scanner)

- Max data rate: 4 million pts/s (2 million each)

- Effective data rate: 2 million pts/s

- Max range: 182 m
- Length resolution: 0.1 mm; noise: 0.2 mm

Panoramic Camera:

- Integrated 360° camera, 24 MP
- Max 8 fps depending on distance setting
- Real-time AI anonymization

GNSS Sensor:

- Integrated GNSS receiver with 555 channels
- Multi-constellation, multi-frequency
- Supports HxGN SmartNet / NTRIP RTK corrections

Software:

Pegasus FIELD: mission planning, control, real-time pre-processing and anonymization.

Cyclone Pegasus OFFICE: post-processing, trajectory adjustment, classification, anonymization, feature extraction, and export (georeferenced point clouds + anonymized photos)

IRI Calculation Software

Atlas DMT + Atlas Road module (v22.12.3)

IRI is computed from the longitudinal profile extracted from the cleaned, georeferenced point cloud. The procedure follows ČSN 73 6175, with verification against ProVAL 3.5.

Metrological Notes

The system is classified as a non-regulated working measuring device. Calibration is performed by the manufacturer (ISO 9001). GRID ensures metrological continuity and regular checks. Full calibration is performed at least every 2 years.

Manufacturer-Declared Accuracy

Without GNSS outage (post-processed):

- Position accuracy: 0.011 m
- Height accuracy: 0.011 m

RTK mode:

- Position accuracy: 0.012 m
- Height accuracy: 0.012 m

After 60 s GNSS outage (post-processed):

- Position accuracy: 0.014 m
- Height accuracy: 0.016 m

Data Structure:

- Minimum density: 2000 pts/m²
- Formats: PTS, LAZ, LAS
- Digital terrain models via Atlas DMT
- IRI outputs: text/table formats and raster color maps.

NCC Infrastructure

NCC Profiler. Delivered by Greenwood Engineering A/S

The Profiler provides both transverse and longitudinal profile, and allows them to be combined in one 3D profile. The Profiler uses high precision point lasers and digital data acquisition, IMU assisted GPS and Right-of-Way Imaging.

An odometer is mounted on the wheel of the vehicle and in combination with the inertial system. Each laser provides a longitudinal roughness profile (IRI) and contributes with one point to the transverse profile. The lasers have a measuring frequency of 32 kHz. Three of the lasers operate at 62,5 kHz for high accuracy MPD measurements.

The Profiler has a high-performance computer with Ethernet network and modular subsystems. The vehicle is operated from the front seat using a keyboard connected to a rack mounted PC in the back of the car, which controls data acquisition and subsystems. The data acquisition software consists of a real-time calculation module capable of capturing and handling output from all sensors at high speeds.

The Swedish National Road and Transport Research Institute (VTI) is an internationally prominent research institute in the transport sector, whose principal task is to conduct research and development related to infrastructure, traffic, transport, and mobility users. The Institute is an assignment-based authority under the Swedish Ministry of Rural Affairs and Infrastructure, dedicated to continuously developing knowledge pertinent to the transport sector and in this way actively contributing to achieving the Swedish transport policy objectives.

Our operations cover all modes of transport, including areas of pavement technology, infrastructure maintenance, vehicle technology, traffic safety, traffic analysis, mobility users , environment, planning and decision making processes, transport economics, and transport systems. Knowledge developed by VTI provides a basis for decisions made by stakeholders in the transport sector. In many cases our findings have direct applications in both national and international transport policies.

VTI conducts commissioned research in an interdisciplinary organization, and also undertakes investigations, consulting services, and various measurement and testing services. The Institute has a wide range of advanced research equipment and facilities, including laboratories for road material testing, measurement technology, crash safety testing, and world-class driving simulators.

The National Transport Library at VTI is a national resource for the supply and dissemination of information in the field of transport research.

VTI cooperates with leading universities in Sweden engaged in related research and education and also continuously participates in international research projects and networks.

The Institute holds the quality management systems certificate ISO 9001 and the environmental management systems certificate ISO 14001. Some of the test methods used in our labs for crash safety, measurement technology and road materials are also certified.

We have about 250 employees at locations in Linköping (head office), Stockholm, Gothenburg and Lund.

vti

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