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PAS 2161: Road Condition Monitoring Trials Report 2025

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Executive Summary

In 2023, DfT collaborated with TRL in an initial study of the comparability of new technologies for Road Condition Monitoring (RCM). The study was conducted on roads in Surrey, where a methodology for comparing RCM categories was established (Road Condition Monitoring Data - Network Study, 2024). The demonstration trial reported here builds on that initial study, establishing the demonstration process for approving technologies for reporting condition on the road network.

The demonstration process involves the collection of data along a predetermined route for three Local Authority's (LAs). The surveys were conducted by road engineers and RCM technologies over 4-week staggered windows. Consultations with LAs were undertaken to identify the suitability for using their network for the trials. Three LAs were chosen considering various criteria, to be as representative as possible of LA roads within England. From this, Cumberland, Essex and Liverpool were selected as the LAs for the trial.

The data collected from within these LAs were reported in the PAS2161 format, where it was analysed against a road engineer dataset. The engineer dataset was constructed using a total of 19 road engineers who were driven around at least one of the routes within the same 4-week staggered windows. The engineers were given instructions on how to report the condition in line with PAS 2161 and were provided with devices to record the condition category for the roads. The MODE category value among the engineers was used as the benchmark dataset to evaluate the performance of the technologies.

The demonstration process also required the provision of repeated measurements over a specified route. This route was a subset of the route for each LA, with technologies being required to provide two additional measurements. These data were used to test the repeatability of the technologies.

A subset of the benchmark data was provided to the technologies to aid calibration to the PAS 2161 requirements. Approximately 20% of the benchmark data across the three LAs was used to make up this dataset. The lengths of road that were chosen to be included in the calibration data contained high agreement by the engineers and included a variety of different condition values. The remainder of the data was withheld for evaluation.

The data from the three LAs were analysed against the engineer benchmark using various statistical analyses, including: precision scores, delta scores, chi-squared statistics, accuracy scores, and others. After the initial analysis, it was identified that the agreement between the providers was less than desired, so a second calibration was used to improve the performance of the technologies. In the second calibration, the Essex engineer data and the distribution of the category values for all three LAs were provided.

The updated datasets from the second calibration process were analysed in an identical way to the initial submission. It was also decided that the agreement between the providers was of high importance, so a provider benchmark was created using a subset of the technologies. This benchmark was created by removing outliers and keeping technologies that had high agreement with each other and the engineer benchmark.

Following the analyses, DfT established the pass criteria for a technology to be considered demonstrated. The criteria included tests for the engineer benchmark, provider benchmark

and repeated route data. These tests aimed to measure the performance of the technology, including its accuracy of reporting condition categories and its consistency. The criteria led to 9 technologies passing the demonstration process, with consequent approval for use on the road network.

Demonstrated Technologies

The technologies listed in Table 1, for the stated providers, have been successfully demonstrated against PAS 2161 and these technologies are approved to deliver RCM data on the local authority classified road network from 26th September 2025 to 31st March 2027.

Table 1 List of demonstrated technologies.

Provider	Technology	Technology Type*
AISIN	Michilog	M
Gaist	Gaist Carriageway Condition	S
Metricell	Inference Model X Human Agent	A
Metricell	Inference Model X AI Agent	M
Route Reports	RouteReports RCM	M
Vaisala	RoadAI	M
WDM	PASWFE	M
XAIS-PTS	MFV AI (SCANNER Accredited device with AI)	S
XAIS-PTS	AEI	E

*Technology Types are defined as per the PAS definitions, as shown in Table 3.

This demonstrated status only applies if the providers continue to use the same methods and contractual arrangements in place at the time of the trials. The current list of successfully demonstrated technologies (until March 2027) along with their certificates can be found on the UKLRG website at the following location: https://ukrlg.ciht.org.uk/ukrlg-home/guidance/road-condition-information/data-collection/pas-2161/

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Thanks also go to the engineers from local authorities who participated in the benchmark data collection (Barnet, Plymouth, Wiltshire, Luton, Lincolnshire, Hertfordshire, Hampshire, St Helens, Knowsley, Wirral, Sheffield, Halton, Northumberland, Derby City, Liverpool, Essex, Cumberland, Westmorland & Furness).

Special thanks go to the Department for Transport (DfT) for funding this research and providing invaluable guidance and advice throughout.

Thanks to all TRL staff that contributed to the work as technical advisors and drivers. Including Martin Greene, Darius Singfield, Jon Grainger, Arnold Cheung, Nigel Hewitt, Patrick Werro and Mark Charlton.

Finally, we wish to thank all the RCM data providers who took part in the demonstration trials, whether they were successfully demonstrated or not.

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Glossary

Term	Definition
DfT	Department for Transport
LA	Local Authority
PAS	Publicly Available Standard
RCM	Road Condition Monitoring
SCANNER	Surface Condition Assessment for the National Network of Roads

1 Introduction

Road Condition Monitoring (RCM) data plays an important role in assessing and managing the condition of road networks. Governments and organisations use RCM data to report the road condition for both local and national reporting.

Since 2009, data collected from dedicated survey vehicles that follow the SCANNER requirements (SCANNER surveys for Local Roads: User Guide and Specification, 2011) have been used for national reporting. However, significant progress has been made in the development of new and alternative technologies that collect road condition data. Due to these advancements, Department for Transport (DfT) established the Publicly Available Standard (PAS) 2161 to allow transition to an approach that is less restrictive on the type of technology used, and to allow greater freedom for LAs to collect road condition data for national reporting (PAS 2161, 2024).

The PAS was published by DfT in collaboration with the British Standards Institution and TRL in 2024 and outlines a new set of condition categories that represent the condition of a length of road in the network. The condition categories are reported in the range 1-5, for each 10m sub-section of the network. Further details of the condition categories can be found in Section 2.1.1 or by following this link: https://knowledge.bsigroup.com/products/road-condition-monitoring-rcm-data-specification

In 2023, DfT collaborated with TRL in an initial study in Surrey which assessed the comparability of new technologies for road condition monitoring (Road Condition Monitoring Data - Network Study, 2024). The study required participating technologies and experienced highway engineers to survey a predefined network and report the road condition using the PAS 2161 one-to-five scale. This study informed the creation of the demonstration process discussed in this report and helped identify suitable technologies to collect PAS 2161 compliant data.

This report outlines the process undertaken in the PAS 2161 demonstration trial in 2025. In Section 2, the methodology of the trial is outlined, this includes information about PAS 2161, selection of local authorities and trial routes, the engineer benchmark data collection, inviting technology providers to participate, data collection and the creation of quality assurance documentation.

In Section 3, the approach for analysis of the benchmark and technology data is outlined, this includes discussion of calibration data, tests used to assess the technologies and the assessment criteria.

In Section 4, some of the limitations and challenges faced during the trial and the actions taken to mitigate their impact are discussed.

2 Methodology

2.1 Trials preparation and benchmark data collection

2.1.1 Road conditions

The demonstration uses the condition categories defined in PAS 2161 as the measure of road condition. The condition is indicated on a scale of 1 to 5, where 1 shows no deterioration and 5 indicates severe deterioration. The definition of the condition categories is provided in Figure 1, where the category value is determined by considering the treatment that would be necessary to restore a particular sub-section to a condition representative of that sub-section when not requiring maintenance.

Category	Description	Potential maintenance treatment option
1	No deterioration	Pavement is not considered for maintenance
2	Minor (and/or aesthetic) deterioration	Light maintenance (e.g. minor patching)
3	Moderate deterioration	Localised intervention or mid-life preventative maintenance (e.g. surface dressing, patching, crack sealing
4	Moderate to severe deterioration	Rehabilitative maintenance, perhaps full carriageway (e.g. resurfacing with thin overlay/surface dressing and multiple patching, edge haunching)
5	Severe deterioration	Structural maintenance (e.g. full carriageway resurfacing or reconstruction)

Note: The examples of maintenance treatment options provide general, not definitive, descriptions of some of the maintenance treatments that might be considered by a typical Highway Authority engineer to restore a length in that RCM condition category to a condition that does not require maintenance. They are provided for guidance only and are non-exhaustive. Benchmarking of categories, and the ability of RCM devices to report them, is established through comparison with consensus assessments of highway engineers (see Annex C).

Figure 1: PAS 2161 Condition Categories, reproduced from PAS2161

For the purposes of the demonstration process, the technology providers were required to provide carriageway scores rather than lane scores. The decision was made as some technologies are unable to provide lane scores, therefore, providing carriageway scores allowed a fair comparison between technologies. The engineers were also instructed to report condition on a carriageway basis. The condition category of the lane in the worst condition was used as the condition category of the entire carriageway. The technology providers were given this information and access to the engineers' instructions to align the reporting methods.

2.1.2 Selecting local authorities for participation in the trials

DfT invited LAs to participate in the trial by hosting the condition surveys on their networks. TRL engaged with interested parties to evaluate their suitability for involvement in the process. As part of the assessment, LAs were asked to provide maintenance schedules covering the trial period, along with condition data for their road networks. This information supported the evaluation process, which considered several criteria, including:

- Diversity of road classification and types, e.g. bridges, one-way carriageways, etc.
- Variety and nature of road defects
- Practical challenges for surveying
- Local terrain characteristics
- Typical weather conditions
- Balance between rural and urban areas
- Representativeness of the LA's road network in relation to the wider network in England

Once a shortlist was established, a comparative assessment was carried out to ensure the trial would cover a broad range of road types and conditions. Three LAs were selected, Cumberland, Essex and Liverpool. Collectively, the three networks covered the widest variety of road types and defects than any other combination. The LAs that were not selected were informed and thanked for their interest in participating.

2.1.3 Selected routes for the trial

TRL engaged with the three participating LAs and developed trial routes using the information provided during the selection process. The trial routes included a selection of roads in the LA's network where the technology providers and engineers could survey and report the PAS 2161 condition categories. For each LA, two routes were created: a main route that was surveyed once by the technology providers, and a repeated route which was a subset of roads from the main route that had two additional surveys (i.e. the repeated route was surveyed three times). The main route was used to assess the performance of the technologies against the engineers' condition assessment, and the repeated route was used to assess the repeatability of the technology. For each local authority, the main routes aimed to contain approximately 100 kilometres of carriageway, with the repeated route containing approximately 25% of the main route, by length.

Various criteria were used to select the routes, these included:

- Presence of all different road condition categories
- Presence of all road classes in approximately equal proportions

- A selection of road sections that could be driven as a continuous, or almost continuous, route
- Avoidance of too many junctions, roundabouts, etc. that would disrupt the flow
- Including roads that would provide challenges to the technologies, e.g. bridges, narrow sections, steep terrain, etc.

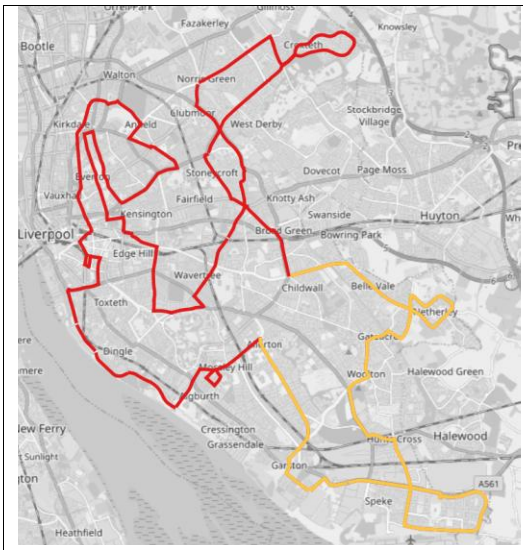
Note that the selection process resulted in samples of the network with distributions that were not fully representative of the distributions of road types or conditions seen in the whole network, but aimed to include sufficient data for each condition category to allow assessments to be made on a diverse road set.

After initial draft routes were created, the LAs were asked to provide feedback on the routes. During this process, certain lengths of road were identified as having planned maintenance interventions before or during the trial window; these lengths were removed and / or altered accordingly. Once the initial routes were established, TRL obtained data along the routes to confirm their suitability to the task in hand. From this data collection, the routes were finalised in agreement with the LAs, and for each route a monitored network definition was created.

The final routes were made in GIS shape files that contained the geometry of the route and information about the sections of the route. The section information included unique road ID, section label, Easting and Northing at the start of the section, Easting and Northing at the end of the section, section length, road classification, section type, section function and number of lanes.

Geometry and section information were obtained from the LA network definitions and modified to improve accuracy and consistency between the LAs. Sections were modified by joining short sections together, improving road geometry to closer align to the road network and changing labelling where appropriate. Additionally, some information, such as number of lanes, was not available from the LAs network definition, so missing data was obtained using TRL survey information.

The trial routes are outlined in Figure 2 to Figure 4.



Main route (including Repeated route):

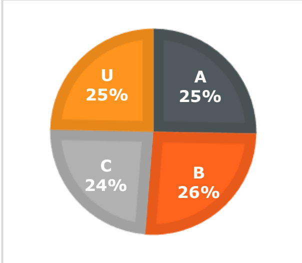
- A – 19.5 km
- B – 20.0 km
- C – 18.5 km
- U – 19.0 km

Total 77.0 km

Repeated route:

- A – 4.3 km
- B – 11.8 km
- C – 1.3 km
- U – 9.4 km

Total 26.8 km



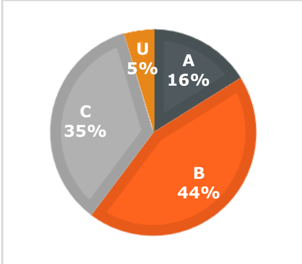
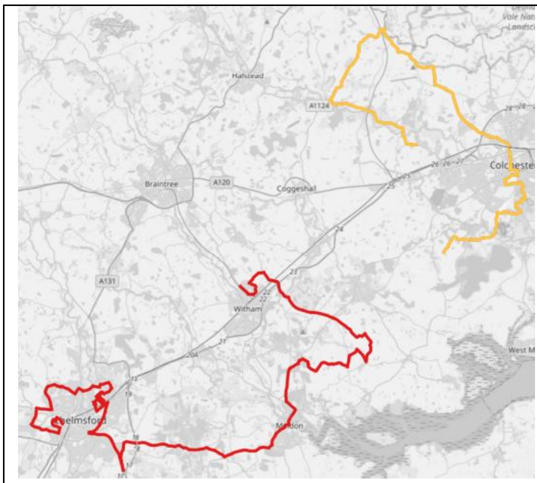


Figure 2 Trial route (red and yellow) and repeated route (yellow) for Liverpool with road classification breakdown by carriageway length.



Main route (including Repeated route):

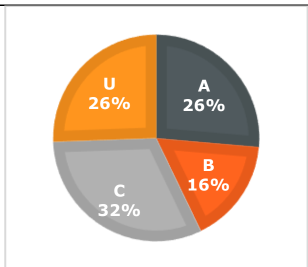
- A – 19.5 km
- B – 21.1 km
- C – 23.7 km
- U –21.6 km

Total 106.3 km

Repeated route:

- A – 7.9 km
- B – 14.4 km
- C – 13.1 km
- U – 6.3 km

Total 41.8 km



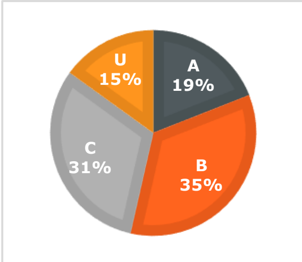


Figure 3 Trial route (red and yellow) and repeated route (yellow) for Essex with road classification breakdown by carriageway length.

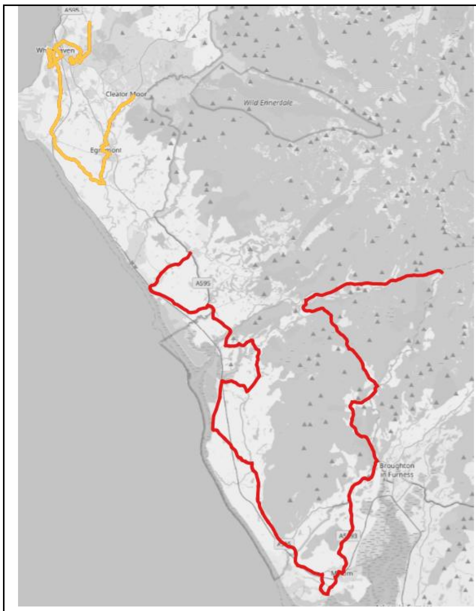
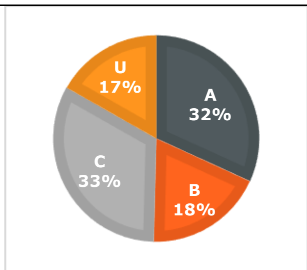
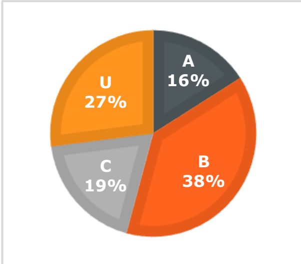
	Main route (including Repeated route): • A – 36.2 km • B – 21.2 km • C – 37.4 km • U – 19.2 km Total 114.0 km Repeated route: • A – 5.0 km • B – 12.0 km • C – 5.9 km • U – 8.5 km Total 31.4 km	 

Figure 4 Trial route (red and yellow) and repeated route (yellow) for Cumberland with road classification breakdown by carriageway length.

2.1.4 Benchmark survey design

The design of the engineer benchmark surveys to establish condition categories for each sub-section was based on the approach used in the Surrey trials (Road Condition Monitoring Data - Network Study, 2024). The aim of the Demonstration was to compare these benchmark categories with the categories reported by the technologies to understand comparability and consistency and ultimately to assess the providers as demonstrated, or not.

Between 7 and 9 engineers surveyed each LA trial network. The benchmark condition category for each sub-section was determined by the consensus of the engineers. This approach helps to mitigate individual differences in judgment and ensures that the benchmark data most accurately reflects the level of condition that would typically be reported by LAs.

The design of the benchmark data collection was as follows:

- An Application (App) for an Android tablet (Figure 5) was used by LA engineers to report condition categories during a driven survey along the trial route
- A GPS device connected to the App recorded the time and location of the engineer during data collection
- Engineers reported their condition category rating as a continuous assessment. Every time that the engineer considered the category to have changed, they recorded a new rating on the tablet.

The data collected from the tablets was processed into the benchmark dataset. The method of processing the engineers' data is outlined in Section 2.1.6.

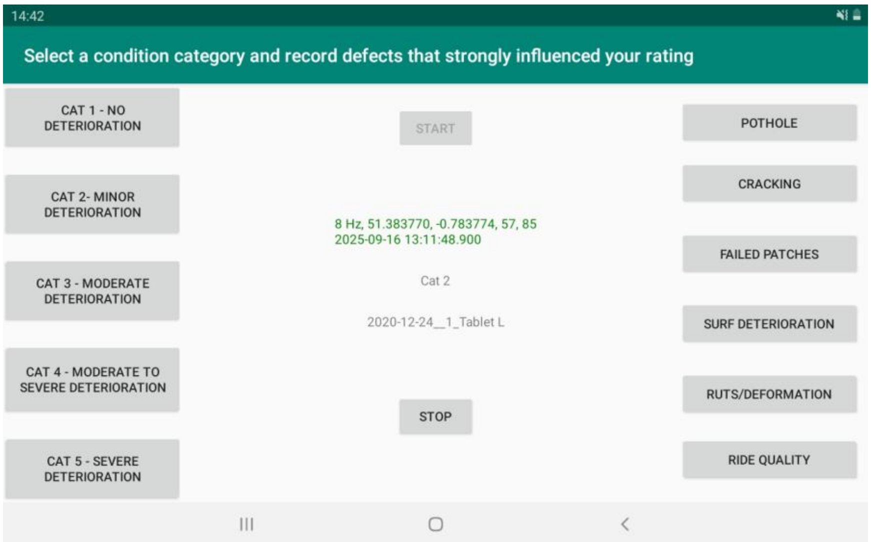


Figure 5 Screenshot of the engineer application that records road condition data for the trial.

2.1.5 Benchmark data collection

The collection of benchmark data for the three routes involved working with the LAs to coordinate the data collection activities, coordinating road engineers to conduct the surveys, and ensuring that the data collected was of appropriate quality for benchmarking purposes. The data collection windows for the technologies and the engineers are provided in Table 2.

Table 2: Data collection survey windows for the demonstration trial.

	Survey Window	Engineer Surveys
Essex	17th March to 2nd May 2025	18th March to 20th March 2025
Liverpool	24th March to 25th April 2025	25th March to 27th March 2025
Cumberland	31st March to 2nd May 2025	1st April to 3rd April 2025

The LAs were asked to, where possible, avoid performing maintenance on the routes during the survey windows. This minimised the risk of the condition of the road being altered throughout the survey window. Once the survey window had passed, the LAs were also asked for information on any maintenance that had occurred during the survey period.

The Essex survey window initially planned to finish on 18th April but was extended due to maintenance that had occurred and / or was occurring on the planned route during the survey window. This necessitated a late change in the final route, so additional time was given to allow the technology providers to adapt to the changes.

DfT requested LAs to provide road engineers for the surveys. A total of 19 engineers took part in the data collection process: 9 in Essex, 8 in Liverpool and 7 in Cumberland, with 5 of these engineers participating in multiple LAs. The engineers were emailed the detailed guidance in Appendix A, prior to data collection. The engineers were also given a briefing on the morning of the benchmark data collection to discuss the purpose of the trial, the equipment for data collection, the engineers' instructions and to answer any questions about the process.

Over the course of a few hours, the engineers were driven around the main trial route by a TRL driver. To ensure comfort and independent assessments during data collection, no more than two engineers were in the vehicle at any one time. Regular breaks were offered every 30 minutes, with a longer lunch break provided to help mitigate the effects of fatigue.

Trial preparation ensured that any tools or software needed to load, process and analyse network RCM data were ready for use and tested ahead of the engineer data collection. Additionally, feedback was sought from the engineers at the end of the data collection stage to understand the process from their perspective, and to gain insights on how the process could be improved if repeated.

2.1.6 Mapping Engineer Data to the Route

The road engineers' data consists of two key components. The first includes the time and condition category linked with each button press. The second consists of spatio-temporal data—time and location—recorded at 0.1 second intervals. These two datasets are combined by assigning a condition category to each spatio-temporal data point based on the timing of the engineers' button presses.

Data points recorded while the vehicle was stationary were excluded. The remaining data was mapped onto the 10m lengths based on the vehicle's direction of travel and distance from each segment. The spatio-temporal data point was assigned to the nearest 10-metre section that met all required criteria. Each 10m length was then assigned a condition category based on the most frequently occurring category among its associated spatio-temporal data points.

A manual review was conducted to verify the accuracy of the mapping. Any necessary adjustments were made based on this assessment, and the final engineer datasets were established. An example of the results of mapping is shown in Figure 6.

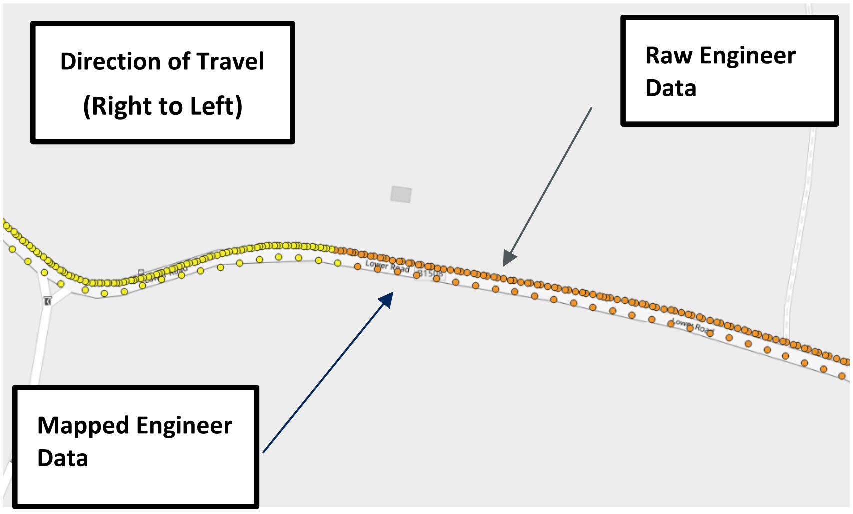


Figure 6 Image of raw and processed engineer data from an engineer in Essex. PAS 2161 condition categories: 1 – Red, 2 – orange, 3 – yellow, 4 – green, 5 – blue.

2.2 Technology provider data collection

2.2.1 Inviting providers

TRL prepared and issued a press release in September 2024, stating that demonstration trials would be held in 2025 and interested parties could contact TRL and DfT to register their interest. There were also follow up postings through TRL's social media and by DfT at events including LCRIG and Strictly Highways. All interested parties were given information about the trials and invited to participate in virtual briefing sessions.

2.2.2 RCM technology types

A range of technologies and methodologies are used to collect RCM data. To clarify the general approaches used by different RCM technologies, PAS 2161 introduced a set of definitions for "RCM technology types." While recognising that new technologies may emerge in the future, current RCM technologies were found to fit into five distinct categories, with a sixth category reserved for potential future developments. These categories are described in Table 3.

Table 3: RCM Technology Types

Type	Description	Notes
A: Application-based mobile technologies	The use of data collection devices, such as mobile phones running applications, but not specifically installed for RCM	Typically obtained via remote access to data collected by applications running on mobile phones, or other similar devices.
E: Engineers' inspections	Driven or walked engineers' inspections	Typically obtained via measurement of condition using dedicated walked or driven engineers' inspections.
M: Dedicated mobile technologies	Individual, mobile, portable data collection devices, typically installed in a vehicle on a temporary or permanent basis specifically for the collection of RCM data	Typically deploying small-scale image collection, such as mobile phone or dash-cam technologies supported by a global navigation satellite system (GNSS), running bespoke applications. Collection is managed/controlled by data collector operatives, or operatives trained in the use of the system.
O: Other technologies	Data collected using data collection devices not able to be described by one of the other types listed	This can include technologies such as remote sensing, aerial, satellite inspections.
S: Dedicated data collection vehicles	Individual vehicles either permanently or temporarily equipped with devices whose primary function is the collection of RCM data	Typically deploying dedicated distance measurement devices and inertial GNSS to provide high locational accuracy, and industrial image, laser profile/LiDAR or other dedicated measurement devices.
V: Vehicle telematics	The use of data collection devices that take the form of vehicle telematics data (provided via instrumentation not specifically installed for RCM)	Typically obtained via remote access to vehicle on-board telemetry data.

2.2.3 Participants

A total of 16 technology providers participated in the demonstration trial, collectively submitting data for 25 distinct technologies. One technology was removed from the process due to an insufficient number of repeated routes.

24 technologies submitted data for both the first and second calibration submissions, while one technology provided data only for the first calibration, resulting in 49 data submissions being considered in the overall demonstration process.

The trial included a range of RCM technology types, broken down in Table 4.

Table 4 The breakdown of technology types that participated in the demonstration trial.

Technology Type	Number of Technologies
A	3
E	1
M	10
O	0
S	10
V	1
TOTAL	**25**

2.2.4 RCM data collection

Prior to data collection, the technology providers were given shape files containing the routes for the trial. These files contained all necessary information required to undertake the surveys for the purposes of the demonstration process. TRL offered support and responded to queries as required about the routes acting as the 'Highway Authority'.

2.2.5 Calibration data

Calibration data was given to the technology providers to assist in calibrating their technologies to the PAS 2161 one-to-five scale. The calibration data was a cleaned subset of the engineer benchmark data containing approximately 20% of the three trial routes (further details of the cleaning process can be found in Section 3.1.2.3). This was provided to the technology providers during the data collection period (on 14/04/25). The calibration dataset was chosen based on the following criteria:

- A variety of road type and condition
- Higher proportion of category 4 and 5 conditions
- Proportional split between the LAs with respect to the routes
- High levels of agreement between engineers
- Some lower levels of agreement between engineers

Some additional data opportunities to improve calibration were identified as part of the initial calibration process. Therefore, additional data was provided to technologies. The additional calibration included the proportions of the condition categories for the full network and all engineer benchmark data for Essex. The second calibration data was provided on the 22 July 2025, with providers initially given two weeks to submit a new dataset; this was extended where necessary on a case-by-case basis.

2.2.6 *Consistency (Quality Assurance)*

To ensure consistency of data from demonstrated technologies between demonstrations, it is necessary for robust Quality Assurance (QA) procedures to be implemented by the RCM provider. This breaks down into the following key parts:

- Monitoring the performance of the technology over time and ensuring that the technology as a whole reports pavement condition consistently between demonstrations. This can include monitoring for drift and need for recalibration, and /or monitoring the need for and impact of replacement of components within the technology.
- Each instance of the technology (e.g. different survey vehicles), remains consistent with each other instance in the data they collect i.e. “fleet consistency” for the technology
- There is a suitable procedure to add new instances of the technology (e.g. new survey vehicle) to ensure that it produces consistent results with the other instances of the technology

The procedures undertaken will differ between the different technology types (technology types are discussed in section 2.2.2) and also may differ between different technologies within the same technology type.

Therefore, it was necessary to obtain details from each RCM provider on the procedures they undertake to maintain consistency in data for each of their technologies. A pre-demonstration questionnaire was developed and distributed to obtain details on the QA that is/will be undertaken for the technology along with other supporting data. On review of the responses, it was identified that some RCM providers misinterpreted the intent of some of the questions or did not provide sufficient detail. These providers were contacted directly with follow-up questions/discussion to obtain the required information.

To cover the broad range of possible technologies required including questions that would not be applicable or appropriate to all technologies. It was found that the inclusion of these questions caused some of the confusion/poor responses discussed above. It was therefore identified that in future this process should be carried out with technology type specific questionnaires. This would reduce the instance of questions that are not appropriate for the technology, and, in addition, it would allow for additional guidance and examples which would be relevant for the technology type. TRL developed some initial versions of these new questionnaires, and it is anticipated that these will be used as the basis for obtaining the QA and other supporting information in any future demonstrations.

3 Analysis

3.1 Approach to Analysis

The methodology for analysing the technologies follows the approach identified in the Surrey Trial in 2024 (Road Condition Monitoring Data - Network Study, 2024). The technologies are assessed by comparing their outputs against two benchmarks: the engineers' benchmark and the provider's benchmark.

- The engineers' benchmark consists of processed data collected from engineers, as outlined in Section 2.1.5 and Section 3.1.2.3.
- The provider's benchmark was developed using a subset of technologies whose outputs showed strong agreement with each other and with the engineers' benchmark. This process is described in section 3.1.2.4.

Before analysis, the technology datasets underwent a processing stage to ensure compliance with the PAS 2161 common file format and reporting requirements. This included:

- Validating the accuracy of location data
- Checking coverage requirements were met
- Confirming the presence and accuracy of all required data fields

While all providers met the reporting requirements, some submissions did not fully conform to the PAS 2161 common file format. In such cases, feedback was provided detailing the issues, and revised submissions were requested.

The technology and engineer datasets were aggregated from 10m to 100m data. The 100m data was used to mitigate the impact of location inaccuracies in the engineer and RCM data.

Three measures were used to evaluate the technologies performance against the two benchmarks: precision, distribution of categories and recall. Additionally, the consistency of outputs for the same road is measured using the repeat route datasets. The definition of the tests can be found in Section 3.1.4.

3.1.1 Aggregating 10m to 100m lengths

The benchmark and technology data were aggregated and analysed on 100m lengths. To obtain the 100m lengths, the max-mode (Equation 1) was taken over all 10m category values in a 100m length. The max-mode is the MODE of the category values, and where there are multiple modes, the maximum condition category was taken. When the road length is not divisible by 100m to an integer value, the additional length is joined at the end of the final 100m length. For example, if a section is 325m long, the road is divided into 0m-

100m, 100m-200m and 200m-325m. These sections are made from the 10m sections (0m-10m, ..., 90m-100m) for 0-100m, (100m-110m, …, 190m-200m) for 100m-200m and (200m-210m, …, 300m-310m, 310m-325m) for 200m-325m.

3.1.2 Benchmark datasets

This section outlines the process for creating the engineer and provider benchmarks. To ensure the reliability and consistency of the benchmarks, a series of data cleaning and validation steps were used and are outlined below.

3.1.2.1 Benchmark Calculation

The engineer and provider benchmark datasets were made by combining the category scores for each 10m length. The max-mode of all reported categories was established as the benchmark. A detailed explanation of the max-mode and the method for obtaining the 100m benchmark can be found in Section 3.1.1.

3.1.2.2 Maintenance-Related Data Removal

Lengths identified as having undergone maintenance within the data collection windows, based on records provided by LAs, were excluded from the dataset. For the 10m benchmark datasets, any section within 10 metres of a recorded repair was removed to account for any location inaccuracies in the maintenance location or the RCM data. A similar approach was applied to the 100m benchmarks, where the 100m section containing the repair, as well as any other 100m sections within 10 metres of the repair, were excluded. This step was required to ensure that the providers and engineers recorded condition on a set of roads in as similar a condition as possible.

3.1.2.3 Engineer Benchmark Development

The engineer benchmark was developed by comparing engineers' data within the same LA at both the 10m and 100m levels. Outlier engineers were identified and removed using a combination of the interquartile range outlier tests and Z-score tests at the 95% confidence level; these tests are defined in Appendix B. Following outlier removal, the level of agreement between each engineer and the updated benchmark was assessed to identify and exclude engineers with low agreement. In total, 5 engineer datasets were removed through this process.

3.1.2.4 Provider Benchmark Development

The provider benchmark followed a similar methodology to the engineer benchmark for outlier detection and removal. However, an additional test was used to compare agreement of the providers data to the engineer benchmark. Where a technology had been submitted multiple times—often due to a second calibration—the version with the highest agreement with both the engineer and provider benchmarks was retained, while the others were excluded to minimise bias. This process resulted in a final provider benchmark comprising 9 technologies.

3.1.2.5 Minimum Representation Threshold

To further improve data quality, any benchmark length where fewer than 74% of the contributing engineers or technologies had recorded data was excluded from the final benchmark. This figure was used in the Surrey trial (Road Condition Monitoring Data - Network Study, 2024) and its suitability was confirmed through further analysis on the required amounts of data for consistent / reliable results. The analysis found that, given the agreement between engineers in the Surrey trial, a minimum of 5 to 6 engineers (including outliers) were required to have a sample representative of the full population. Hence, given 7 to 9 engineers surveyed each route, the threshold was deemed suitable for the demonstration trial.

3.1.2.6 Distribution of Benchmarks

The distribution of category values for each of the benchmarks can be seen in Figure 7 and Figure 8.

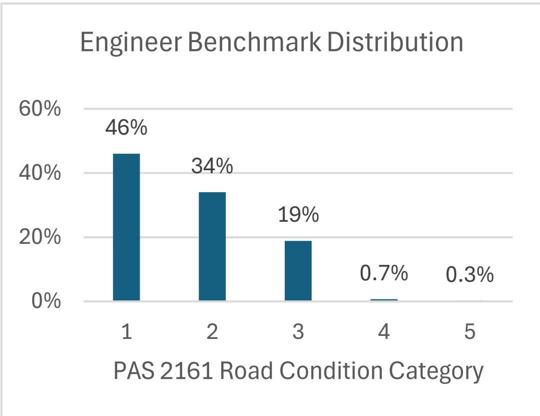


Figure 7 Proportion of 100m lengths in the PAS 2161 condition categories for the engineer benchmark.

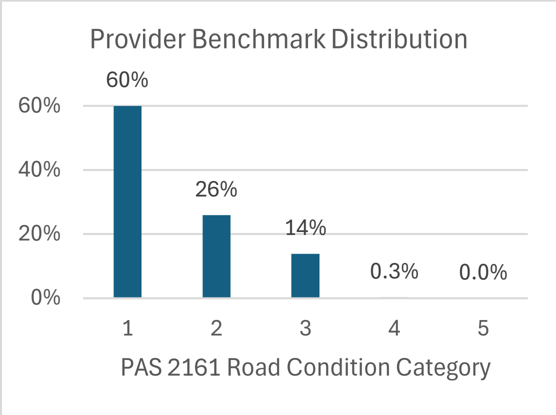


Figure 8 Proportion of 100m lengths in the PAS 2161 condition categories for the provider benchmark.

3.1.3 Calibration data

The calibration data was given to the providers at the 10m level, with the expectation that they would utilise the data in a way that extracts the best value for their technologies. There were two calibration datasets provided: the first containing approximately 20% of the engineer benchmark data that was representative of the whole engineer benchmark, and the second containing the full Essex engineer benchmark and the distribution of categories for the full engineer benchmark, given in Figure 6.

The first calibration dataset was 53.779km in length and aimed to have a distribution of categories similar to the full dataset, except for categories 4 and 5, where higher proportions of these categories were provided. More category 4 and 5's were provided to aid technologies in identifying the higher condition categories, as these appeared less frequently on the trial routes. The breakdown of the condition categories by LA for the first calibration dataset is shown in Table 5.

Table 5 The distance and percentages of the trial route road condition categories for each local authority.

(km)	1	2	3	4	5
Cumberland	9.40	6.69	3.31	0.29	0.00
Essex	11.55	5.68	3.18	0.91	0.19
Liverpool	6.25	2.76	2.99	0.50	0.08
Total	27.20	15.13	9.49	1.70	0.27
%	50.57%	28.13%	17.64%	3.16%	0.50%

The calibration dataset was designed to have approximately equal proportions of all four road classifications in each LA. The breakdown of the road length in the first calibration dataset, by classification and LA can be seen in Table 6.

Table 6 The distance and percentage of road classes on the trial route for each local authority.

(km)	A	B	C	U
Cumberland	4.28	4.46	6.36	4.59
Essex	6.84	4.57	5.36	4.75
Liverpool	3.83	3.20	2.76	2.79
%	27.79%	22.74%	26.92%	22.56%

In the benchmark dataset each road classification had different proportions of condition categories, with road classes A and B typically having better condition and road classes C and U typically having worse condition. Therefore, to the best of our ability, this distribution of condition categories within each road classification was maintained in the calibration data. There was an exception for high condition categories, where the aim was to include higher proportions of these sections to ensure a reasonable number of category 4 and 5 road sections were included. The breakdown of the condition categories by road classification in the calibration data is presented in Table 7.

Table 7 The distance of the condition category by road type for the trial route.

(km)	1	2	3	4	5
A	9.37	3.75	1.74	0.08	0.00
B	5.59	3.88	2.51	0.17	0.08
C	7.30	4.38	2.54	0.26	0.00
U	4.94	3.12	2.69	1.19	0.19

The second calibration contained the full engineer benchmark for the Essex route and the proportions of the categories for the full engineer benchmark. DfT made the decision to give the Essex LA as it allowed a larger amount of data to be given to the providers, while still maintaining sufficient data for evaluation, compared to giving a flat percentage of the whole network. Additionally, Essex had the most diverse network, including rural and urban areas, which would allow for better calibration.

The proportion of each condition category in the engineer benchmark is shown in Figure 7. The decision to provide the distribution data was taken due to some providers' first submissions having distributions that were not very comparable to the engineer benchmark. The additional information enabled providers to assess how they compared to the benchmark and, where needed, adjust calibration to better align to the PAS 2161 condition categories.

3.1.4 Performance Tests

Six measures of performance were used in the assessment criteria. They aimed to assess the technologies accuracy in producing the PAS 2161 one-to-five scale and the repeatability of measurements.

3.1.4.1 Precision 0

The percentage of reported 100m road condition categories that match the benchmark exactly. This metric is appropriate because it directly measures strict accuracy, which is the most fundamental requirement when evaluating classification performance. It provides a clear, interpretable indicator of how often the technology matches the reference without tolerance. The calculation can be found in Appendix B in Equation 5.

3.1.4.2 Precision 1

The percentage of reported 100m road condition categories that either match the benchmark exactly or differ by only one category. Precision 1 was selected to complement Precision 0 since PAS 2161 categories represent an ordinal severity scale, where small deviations may still be operationally acceptable. Precision 1 therefore provides a more forgiving but still meaningful accuracy measure that reflects real-world expectations: slight disagreements may not materially affect decision-making. This metric is particularly useful when the benchmark itself may contain borderline cases. The calculation can be found in Appendix B in Equation 6.

Example: If the technology records category 2 and the benchmark records category 1, this is marked as suitable under this test. However, if the technology recorded category 3 instead, this is marked as unsuitable.

3.1.4.3 Pearson Chi-Squared test

The Pearson chi-squared test metric estimates the difference between the benchmark category frequencies and the technology's category frequencies, with a smaller value suggesting the technology and the benchmark are a closer match. The Pearson chi-squared test was included to assess whether the overall distribution of categories produced by the technology differs significantly from the distribution in the benchmark. This test is appropriate because:

- it evaluates differences between categorical frequency distributions
- it helps identify systematic bias, such as a tendency to over- or under-report certain categories

A smaller chi-squared value indicates stronger alignment with the benchmark distribution. The calculation can be found in Appendix B in Equation 7.

3.1.4.4 Macro Recall

The recall for a given category is the count of the reported 100m subsections that match the benchmark in the category divided by the count of the benchmark in the category. Macro

Recall is then the average recall over all categories. This test is appropriate because some road condition categories may be rare, and simple accuracy metrics can be dominated by the most common classes. By averaging recall across categories, Macro Recall gives equal importance to all condition levels, ensuring that performance is not inflated by majority classes. The calculation can be found in Appendix B in Equation 8.

3.1.4.5 Consistency Test – Exact Match

The percentage of the repeated route where the reported 100m category values match for all three datasets. This test measures the reliability of the technology under identical conditions. High consistency indicates stable performance and low sensitivity to environmental variation. The calculation can be found in Appendix B in Equation 9.

3.1.4.6 Consistency Test – None Match

The percentage of the repeated route where none of the reported 100m category values match for all three datasets. This is a stringent indicator of instability and helps highlight lengths where the technology produces erratic results. This test helps identify worst-case repeatability behaviour that might not be visible through average-based metrics alone. The calculation can be found in Appendix B in Equation 10.

3.1.5 Assessment Criteria

The assessment criteria were chosen to evaluate the technologies performance in three aspects:

- accuracy in predicting the PAS 2161 condition categories,
- the distribution of category scores, and
- their repeatability in category prediction on the same roads.

The 6 measures of performance were used over 10 tests to establish the passing criteria for the demonstration trial. The benchmark, test name and passing threshold can be seen in Table 8.

For the assessment criteria, there are required (shown by an asterisk in Table 8) and non-required tests (shown by no asterisk). To pass the demonstration process, the technology must have met all the passing thresholds for the required tests and have passed at least 2 of the four non-required tests.

Table 8 Assessment Criteria of the 2025 PAS 2161 demonstration trial.

Test Data	Test Name	Required	Passing Threshold
Engineer Benchmark	Precision 0	*	≥ 60%
	Precision 1	*	≥ 90%
	Chi-Squared Test		≤ 250
	Macro Recall		≥ 40%
Provider Benchmark	Precision 0	*	≥ 60%
	Precision 1	*	≥ 90%
	Chi-Squared Test		≤ 250
	Macro Recall		≥ 40%
Repeat Data	Consistency – All Match	*	≥ 50%
	Consistency – None Match	*	≤ 5.0%

Several factors were considered when determining the passing thresholds:

- Identification of natural breaks in performance data
- Stricter thresholds applied to higher-priority tests (e.g., Precision 0)
- Consideration of the number of technologies meeting the criteria, while maintaining data quality and comparability

The primary objective was to establish thresholds that meet the need for national reporting. The final thresholds outlined in Table 9 were chosen by DfT and led to 9 technologies passing the demonstration trial.

Table 9 List of the number of technologies that passed each test out of 49 submissions.

Data	Test Name	Technologies passed
Engineer Benchmark	Precision 0	20
	Precision 1	34
	Chi-Squared Test	33
	Macro Recall	20
Provider Benchmark	Precision 0	25
	Precision 1	31
	Chi-Squared Test	30
	Macro Recall	24
Repeat Data	Consistency – All Match	38
	Consistency – None Match	38

Most technologies had two submissions for their technology: one trained on the first calibration dataset and another trained on the first and second calibration datasets. Therefore, there were instances where the first and second submission from a technology passed the assessment criteria for the trial. In these instances, the data submission for a technology that performed better determined that this technology and associated data processes were a PAS 2161 demonstrated technology, and the other submission failed due to having a better performing version of the technology. The highest precision score was used to determine the best performing submission.

3.1.6 Post-Assessment

After the trial, the providers were given technology reports about their performance against the thresholds to help them identify how they can improve their performance for future trials. The passing providers were also given certificates, showing demonstration and approval for use on the network between the shown dates.

Additionally, where submissions of the pre-trial questionnaire were unsatisfactory, technologies were required to provide further responses on quality assurance to ensure that where suppliers have multiple pieces of equipment, or a fleet of the technology, these are producing consistent, comparable and reliable outputs.

4 Limitations

As with any new process, the demonstration trial faced several challenges. Where possible, the trial design was adapted to mitigate the impact of these limitations. This section outlines the key issues and the actions taken to mitigate their impact.

4.1 Engineer Benchmark Data

There were some challenges in ensuring the consistency of the engineers in reporting categories. To mitigate this, several measures were implemented:

- Improving and updating engineer guidance documentation
- Scheduled regular breaks to reduce fatigue
- Exclusion of outlier engineers from the benchmark dataset
- Investigation into areas of low agreement between engineers
- Having a number of engineers survey multiple networks to ensure some consistency between sites
- Use of the same trial facilitator across all three sites to ensure consistent briefing and information delivery

Following these efforts, some small inconsistencies remained between the engineers. However, these were limited in scope, and the majority of the network showed consistent reporting, resulting in minimal overall impact.

4.2 Maintenance

Throughout the design and implementation of the trial, actions were taken to try to reduce the number of repairs that were undertaken on the trial routes. This was required so that the engineers and technologies were assessing the network in as similar a condition as possible. These actions included:

- Using maintenance schedules to inform route design
- Sharing trial routes with LAs and requesting them to avoid maintenance on the trial route, where safe to do so

However, despite these mitigations, some maintenance was performed on the trial route during the trial period. All lengths that were maintained during the trial window were removed from the analysis. Further details of this removal can be found in Section 3.1.2.2.

4.3 Provider Benchmark Data

Using provider benchmarks introduces a potential bias, as included technologies may have a performance advantage. To avoid bias in the inclusion of the providers, a process and thresholds were established prior to calculation of the benchmark to not influence which technologies were included. In this process, the inclusion was based on the alignment of the engineers and the provider benchmark. This was to ensure baseline truth in the provider benchmark via the engineer benchmark to ensure its reliability and consistency.

4.4 Engineer and Provider GPS Route Mapping

GPS inaccuracies can arise from various environmental factors such as tall buildings, tunnels, or adverse weather. These discrepancies may result in misalignment between engineer and provider data, even when road conditions are correctly evaluated. To reduce this risk, the following measures were taken:

- Aggregation of data into 100m segments
- Use of high-precision GPS devices by engineers
- Manual validation of engineer GPS data to ensure accurate mapping
- Investigation of technology data to identify any consistent misalignment of categories

4.5 Calibration data

Because calibration data formed part of the network used to assess RCM technologies, there was a risk of inflated performance results that do not translate to the whole network. To minimise the impact, long continuous lengths were provided in the calibration data to allow parts of the route to have minimal or no calibration data influencing condition score. Additionally, the Essex dataset was removed from the dataset used to assess the performance of the technologies, as the entire network was given in the calibration data. These actions helped preserve the independence of the calibration data and the test data, ensuring a more accurate representation of technology performance.

Additionally, there is a risk of overfitting technologies to the network – performing well on the benchmark dataset but failing to generalise across the wider network. Overfitting occurred in the Surrey trial (Road Condition Monitoring Data - Network Study, 2024) and so additional measures were used in the demonstration trial to reduce the likelihood of overfitting. One measure was giving small proportions of the benchmark data as calibration to the providers, as providing higher proportions of data increases the risk of overfitting. Another measure used was having a diverse range of assessment criteria to evaluate the performance in multiple ways. This enabled the overfitted technologies to be more easily detected, as overfitted technologies often underperform on at least one area, such as distribution or accuracy when tested on unseen data.

References

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Appendix A Engineer instructions

An excerpt of the engineer instructions can be found below. Further information can be provided upon request.

Condition category assessments will be made using the Tablet/App provided. To make an assessment you press the button that reflects your opinion of the condition category of the pavement of the carriageway visible to you. As you are driven along the route you will record a new category on the App when (in your opinion) the condition category of the pavement changes. Therefore, you are rating the pavement condition on a continuous basis, changing the allocated category as the condition changes along the length of the network.

Note:

- To avoid the risk of attempting to record the categories at an overly high level of detail, we recommend that you approach the survey from the mindset "of planned maintenance and scheme identification", but do not attempt to include prioritisation into your rating. Hence such a survey would not expect report "rapid" changes in condition categories (i.e. over very short lengths).
- When assessing the condition category, you should rate the condition of the whole carriageway pavement as a combined rating for multiple lanes. Where lane condition differs, the reported value shall be for the worst lane of the carriageway. For a two-lane dual carriageway, the condition should be interpreted for both of the running lanes in the direction of travel, with the worst selected. For a two-way single carriageway road, the condition should be interpreted for the lanes in the direction of travel and the reverse direction of travel, with the worst selected. E.g. for a two-way single carriageway with condition 1 for the lefthand lane and condition 3 for the righthand lane, the condition for the combined carriageway section should be condition 3.
- The condition of Roundabouts SHOULD NOT be assessed.
- The condition of junctions SHOULD be assessed e.g. the centre area between traffic lights.

Your ratings should be undertaken "out of context". Hence you would not place a length in a poorer condition category (i.e., give it more significant maintenance) because it is in "this location" than if it was located in a "different" location. In summary, assessments should not be influenced by:

- The strategic priority of the road e.g. A main artery A road of high strategic importance showing the same deterioration as an A road of low strategic importance would have the same requirements to restore it to a condition that does not require maintenance.
- The location or environment of the road, e.g. Urban or rural are treated the same – they have the same requirements to restore to a condition that does not require maintenance.
- The volume or types of traffic that the road is taking.

- Maintenance prioritisation and other asset management considerations, e.g., whether that length may have a higher priority (due to any of the above items or for other reasons). This includes the concept of “asset sweating” in which maintenance may be delayed in order to get the maximum life from the pavement.

However, when determining the condition category you should take into account the type of pavement being assessed, when thinking about the level of work needed to restore it to a condition that does not require maintenance, e.g. an A road may have had better ride quality than a U road. You would not expect to restore the U road to a level that is better than when it was new, or restore a U road to the level of ride quality that would be expected of an A road – hence this should be taken into account when rating the condition category.

It will not be practical during the study to provide road class definitions of all the lengths being surveyed (i.e. engineers may not know if this is a A, B, C or U road), you should use your best judgement where it is not clear from signage.

Appendix B Test Definitions

Equation 1 Definition of Max-Mode calculation

$$Max[Mode(\boldsymbol{x})]\,, \qquad (1)$$

where $\boldsymbol{x} = (x_1, x_2, \cdots, x_k)$ is a vector containing condition categories x_i, $Mode$ returns the values that occur most frequently in the vector and Max returns the largest value.

Equation 2 Z-score test statistic

$$\frac{x - \mu}{\sigma}, \qquad (2)$$

where x is the count of the quantity of interest, μ is the mean count of the population and σ is the standard deviation of the mean count of the population. The value x is deemed an outlier at the ~95% level if the absolute value of the Z-score statistic is greater than 2.

Equation 3 IQR outlier test

$$[\mu \pm 1.5 \times IQR(\boldsymbol{x})], \qquad (3)$$

where $x = (x_1, x_2, \cdots, x_k)$ is a vector of the sample values, $IQR(\boldsymbol{x}) = \boldsymbol{P_{75}} - \boldsymbol{P_{25}}$ is the interquartile range (i.e. the difference between the 75th and 25th percentile values) of the sample and μ is the mean of the sample. A value in the sample is deemed an outlier if it lies outside the bounds.

Equation 4 Kronecker delta function

$$x_{i,j} = \begin{cases} 1, & if\ i = j, \\ 0, & if\ i \neq j.' \end{cases} \qquad (4)$$

Equation 5 Precision 0

This statistic measures the percentage of reported condition categories on each 100m road section that matched the benchmark exactly:

$$\frac{1}{n}\sum_{i=1}^{n} \delta_{x_i, y_i}\,, \qquad (5)$$

where n is the number of assessed road lengths, x_i is the technologies PAS 2161 condition category for the 100m subsection i, y_i is the benchmark PAS2161 condition category for the 100m subsection i and $\delta_{a,b}$ is the Kronecker delta function.

Equation 6 Precision 1

Precision 1 measures the percentage of reported condition categories on each 100m road section that matched the benchmark exactly or was within one category of the benchmark:

$$\frac{1}{n}\sum_{i=1}^{n}\left[\left(1-\delta_{x_i,-1}\right)\left(1-\delta_{x_i,0}\right)\left(\delta_{x_i,y_i}+\delta_{x_i-1,y_i}+\delta_{x_i+1,y_i}\right)\right], \tag{6}$$

where n is the number of assessed road lengths, x_i is the technologies PAS 2161 condition category for the 100m subsection i, y_i is the benchmark PAS2161 condition category for the 100m subsection i and $\delta_{a,b}$ is the Kronecker delta function. The first two terms of the summation $\left(1-\delta_{x_i,-1}\right)\left(1-\delta_{x_i,0}\right)$ are used to remove where RCM categories are invalid (-1) or could not be measured (0).

Equation 7 Pearson chi-squared test

The Pearson chi-squared test metric estimates the difference between the benchmark category frequencies and the technology's category frequencies, with a smaller value suggesting the technology and the benchmark are a closer match.

$$\sum_{i=1}^{5}\frac{(O_i-E_i)^2}{E_i}, \tag{7}$$

where $O_i=\sum_{j=1}^{n}\delta_{x_j,i}$ is the observed frequency for the condition category at the 100m subsection i, $E_i=\sum_{j=1}^{n}\delta_{y_j,i}$ is the expected frequency for the condition category at the 100m subsection i, n is the number of assessed road lengths, x_j is the technologies PAS 2161 condition category for the 100m subsection j, y_j is the benchmark PAS2161 condition category for the 100m subsection j and $\delta_{a,b}$ is the Kronecker delta function.

Equation 8 Macro Recall

The recall for a given category is the count of the reported 100m subsections that match the benchmark in the category, divided by the count of the benchmark in the category. Macro Recall is then the average recall over all categories.

$$\frac{1}{5}\sum_{i=1}^{5}\left(\frac{1}{E_i}\sum_{j=1}^{n}\delta_{y_j,i}\delta_{x_j,y_j}\right), \tag{8}$$

where $E_i=\sum_{j=1}^{n}\delta_{y_j,i}$ is the number of 100m lengths of road in condition category i for the benchmark, x_j is the technologies PAS 2161 condition category at the 100m road length j, y_j is the benchmark PAS2161 condition category at the 100m road length j and $\delta_{a,b}$ is the Kronecker delta function.

Equation 9 Exact Match – Consistency Test

The 'Exact Match' consistency test provides the percentage of times that each 100m subsection in the repeated route was given the same condition category in all three datasets.

$$\frac{1}{m}\sum_{j=1}^{m}\delta_{x_{1,j},x_{2,j}}\delta_{x_{2,j},x_{3,j}}\,, \tag{9}$$

where m is the number of 100m assessed road lengths in the repeated route, $x_{i,j}$ is the technologies PAS 2161 100m condition category in repeat route submission i at repeat route length j and $\delta_{a,b}$ is the Kronecker delta function.

Equation 10 None Match – Consistency Test

The 'None Match' consistency test provides the percentage of 100m subsections in the repeated route where none of the reported condition categories of these subsections match all three datasets.

$$\frac{1}{m}\sum_{j=1}^{m}\left[\left(1-\delta_{x_{1,j},x_{2,j}}\right)\left(1-\delta_{x_{1,j},x_{3,j}}\right)\left(1-\delta_{x_{2,j},x_{3,j}}\right)\right], \tag{10}$$

where m is the number of 100m assessed road lengths in the repeated route, $x_{i,j}$ is the technologies PAS 2161 100m condition category in repeat route submission i at repeat route length j and $\delta_{a,b}$ is the Kronecker delta function.

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