THE FUTURE OF TRANSPORT

CLIENT PROJECT REPORT CPR4016

Benchmarking the condition of highway networks

National Highways, Welsh Government, Transport Scotland, and Rijkswaterstaat

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Disclaimer

Executive summary

TRL was commissioned by the Office of Rail and Road (ORR) to benchmark the condition of road surfaces on the Strategic Road Network (SRN) in England (operated by National Highways) against suitable comparator networks. This study follows on from a feasibility assessment undertaken by TRL and CEPA for ORR in 2019 (TRL and CEPA, 2019).

To undertake this study, road surface condition information was collated from the networks operated by National Highways (NH), Transport Scotland (TS), the Welsh Government (WG), and Rijkswaterstaat in the Netherlands (RWS). A parallel exercise was also undertaken to compare road surface condition between parts of NH network and a selection of local road networks in England. This report details the methodology and results of the study.

The measurement of road surface condition incorporates a range of different parameters that together describe its functional and structural condition. The condition parameters assessed in this work are summarised below. In the study these condition parameters were considered independently, rather than aggregating them into a single condition indicator (such as the Pavement Condition Key Performance Indicator[1] used by NH).

	Condition parameters	Notes
Ride quality	3m and 10m enhanced Longitudinal Profile Variance (eLPV), and International Roughness Index (IRI)	Ride quality parameters describe the longitudinal profile of the road surface. Higher levels of these parameters are linked with a poorer experience of ride quality by the road user.
Rutting	Maximum rut depth	Rutting describes the transverse deformation (distortion of the road surface across its width) of the road surface within the wheel paths. Higher levels of rutting can affect vehicle stability and can indicate issues in the pavement structure.
Texture depth	Sensor Measured Texture Depth (SMTD) and Mean Profile Depth (MTD)	Texture depth describes the roughness of the road on the millimetre scale. Texture depth is important for vehicle safety as texture helps in removing water from the tyre/surface interface. This aids in the generation of high-speed friction[2].
Skid resistance	Characteristic Skid Coefficient (CSC), Mean Summer Skid Coefficient (MSSC) and SideWay Force (SWF)	Road / tyre friction describes the friction generated between a tyre and the road surface. Skid resistance is a characterisation of the road surface contribution to road / tyre friction. These skid resistance parameters generally correlate to low-speed friction.
Cracking	Cracking intensity (some authorities).	Cracking suggests fatigue of the surface and/or structure and allows water ingress to the lower layers of the road surface.

[1] A description of National Highways' Pavement Condition KPI can be found in the company's Operational Metrics Manual (National Highways, 2021).

[2] It should be noted that pavement permeability / porosity also performs this function.

The **methodology** used in this work can be summarised as:

- Performing a national benchmarking study that compared the distributions of road condition parameters reported on each of the networks, to show the degree of agreement between these distributions.
- Investigating the condition parameters for each national network in the light of the 'in-service requirements' (the requirements against which the condition of the network is maintained by each road authority)[3].
- Performing a 'deeper dive' into the parameters using additional explanatory variables (such as trafficking) to understand the level of explanatory power of these additional explanatory variables on any differences observed between the parameter distributions on the networks.
- Comparing the condition of a selection of sub-networks[4] of the SRN with the corresponding local authority network. For example, comparing the condition of Cumbria's local authority network with NH managed roads located in Cumbria.

The **summary results** of the national benchmarking exercise have demonstrated that:

- There are no *substantial* differences between the UK national networks for ride quality. However, the NH network provides smoother ride quality (lower 3 and 10m eLPV) than comparable local authority networks.

  The RWS network provides smoother ride quality (lower IRI) than the UK networks. It is noted that the RWS in-service requirements for ride quality are more demanding than those in place in the UK. However, this did not fully explain the differences in network condition, as both the UK and RWS networks appear to be maintained to a level that exceeds their in-service requirements.

  A deeper dive into traffic and material type also did not provide a strong explanation for the differences in ride quality. The RWS network is extensively surfaced with porous asphalt, which is not used in the UK. However, the subset of materials used on the RWS networks that are used on the UK networks also have higher levels of ride quality. It is noted that the ages of the surfaces on the RWS network are lower, which could provide a partial explanation of the differences in condition. In other words, road surface renewals on the RWS network are undertaken more frequently than on the UK networks and thus ride quality is better.
- Substantial differences in rutting are observed between the RWS/NH (lower levels of rutting) and WG/TS (higher levels of rutting) networks. An assessment of the in-service requirements did not explain this observation. The results of the deeper dive suggest that both material type and age at least partly explain the differences in condition.

[3] For the IRI parameter UK requirements have been estimated based on the 3m and 10m eLPV requirements.

[4] Namely; Cumbria, Humberside (Comprising; East Riding, North East Lincolnshire, Hull, and North Lincolnshire), Kent, Norfolk, Nort Yorkshire, Shropshire, and Sommerset.

When the assessment of rutting was broken down by carriageway type it was found that motorways and dual carriageways demonstrated a higher level of agreement between the networks.

The NH network provided lower rutting values than comparable local authorities.

- Differences were observed in the skid resistance of the networks. However, after the in-service requirements were taken into account (i.e. by plotting the distribution of differences from in-service requirement), a better agreement between the performances of the networks was observed.

  Skid resistance is the only parameter for which the consideration of in-service requirements brought the condition of the networks into alignment, and suggests a similarity in the management of skid resistance between the networks.

  However, the RWS network does provides higher skid resistance values than the NH network. The deeper dive analysis did not explain this difference. It is hypothesised that it arises from the porous asphalt materials on the RWS network offering a greater intrinsic skid resistance than the UK's more dense materials. However, as for ride quality, skid resistance values on the RWS network were higher than the NH network even for sections constructed of the same material.

  The NH network provided higher skid resistance values than the Humberside local authority network, but had skid resistance values largely comparable to the Norfolk local authority network.

- The RWS network has lower texture depths than the UK networks, which is not explained by the deeper dive. However, this may be explained by RWS not having an in-service requirement for texture.

  On the whole, the NH network provided higher texture depth values than comparable local authorities.

Understanding differences in network condition - The outcomes of this work suggest that consideration of individual additional explanatory variables (e.g. age, total trafficking, or material type) does not fully explain the differences in network condition observed in the national benchmarking. The deeper dive suggested that further insight might be obtained by analysing thee variables in combination (e.g. by material type *and* material age).

These observations demonstrate that the contribution of different factors is complex, and hence there may be a need for more complexity in the analysis to achieve more explanatory power. It is suggested that such an assessment could be carried out in three ways:

- Extending the deeper dive by testing additional explanatory variables in combination with each other. For example, material type could be further split by age, trafficking rate, or operational environment.
- Further explanatory variables could be collected to provide deeper insight. For example, the NH database holds information relating to road construction (material type and layer thickness) - variables that could influence parameters such as ride quality and rutting. Explanatory variables could also be sought relating to material properties such as aggregate size, polished stone value, or bitumen type (for asphalt surfaces).

- Parameter data could be collected using tools allowing for a like for like comparison of road condition. For example, cracking and fretting on the TS, WG, and RWS networks could be characterised using a single survey method, allowing for a like for like comparison with the NH network, to overcome the difficulties that were encountered when making comparisons in this work.

Maintenance Strategy and the application of in-service requirements – The in-service requirements appear to provide some insight into the reasons for the similarities and differences between networks. Further insight could be gained through an investigation of these requirements, and how they are linked to asset management strategies and policies within the wider context of the management of the networks. Such policies and strategies will influence all parameters, and further insight could help understand the differences seen in this work. This further work could include:

- Achieving a better understanding of the methodologies through which the in-service requirements are applied. This could include literature and organisational review to better understand the organisational oversight and reporting, management structure, sub-contracting procedures, and funding streams etc; interviewing, surveying, or conducting workshops with stakeholders to understand the policies, strategies, and funding arrangements that drive condition management.
- Carrying out assessment of case studies from real sites. These sites could be assessed through the policies of each NRA, and the maintenance decisions compared so that the ‘on-the-ground’ effects of each policy could be understood. For each case study site, hypothetical maintenance regimes would be designed based on the asset management strategies and in-service requirements of each of the comparator road authorities. This approach could be used as a basis for comparing the relative cost of the maintenance approaches and modelling the ‘on the ground’ impact on pavement condition.

Abbreviations and Acronyms

CSC	Characteristic Skid Coefficient
CW	CarriageWay
eLPV	enhanced Longitudinal Profile Variance
HAPMS	Highways Agency Pavement Management System
IL	Investigatory Level
IRI	International Roughness Index
KPI	Key Performance Indicator
LA	Local Authority
LW	Length Weighted
MPD	Mean Profile Depth
MSSC	Mean Summer Skid Coefficient
NH	National Highways
NRA	National Road Authority
PSV	Polished Stone Value
ORR	Office of Rail and Road
RWS	RijksWaterStaat (NRA for the Netherlands)
SC	Skid Coefficient
SCANNER	Surface Condition Assessment for the National Network of Roads
SCRIM	Sideway-force Coefficient Routine Investigation Machine
SFC	Side Force Coefficient
SKM	SeitenKraftMessverfahren
SR	Skid Reading
SRN	Strategic Road Network
SMTD	Sensor Measured Texture Depth
SWF	Side Way Force
TRACS	Traffic Speed Condition Survey
TS	Transport Scotland
TSCS	Thin Surface Course System
WebTRIS	Highways England Traffic Information System
WG	Welsh Government

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1 Introduction

TRL was commissioned by the Office of Rail and Road (ORR) to undertake benchmarking of the condition of pavements on the Strategic Road Network (SRN) in England (operated by National Highways) against suitable comparator networks. This study follows on from a feasibility assessment undertaken by TRL and CEPA for ORR in 2019 (TRL and CEPA, 2019).

To undertake this study, road surface condition information was collated from the national networks of:

- England, operated by National Highways (NH) and consisting of the English Strategic Road Network (SRN) (approximately 12,000 lane km were assessed);
- Scotland, operated by Transport Scotland (TS) and consisting of the Scottish trunk road network (approximately 7,000 lane km were assessed);
- Wales, operated by the Welsh Government (WG) and consisting of the Welsh trunk road network (approximately 3,000 lane km were assessed); and
- The Netherlands operated by Rijkswaterstaat (RWS) and consisting of the Netherlands trunk road network (approximately 7,000 km were assessed).

A parallel exercise has also been undertaken to compare road surface condition between parts of the English SRN and a selection of local road networks in England.

A full description of the data gathering procedures is available in Appendix A. A comparison of network condition has been undertaken to achieve the following objectives:

- To compare the distributions of road condition parameters for each of the networks, and to evaluate the degree of agreement between these distributions. Also, to investigate the condition parameters for each national networks in the light of the in-service requirements for those parameters defined by each national road authority – Section 2.2.
- To perform a deeper dive into the parameters[5] to understand the level of explanatory power of these parameters on any differences observed between the networks - Section 5.
- To compare distributions of condition of sub-networks of the SRN with the distributions for corresponding local authority networks[6]. For example, comparing the condition of the Cumbria local authority network with the SRN sub-network located in Cumbria - Section 6.

The summary observations and conclusions of the study are then presented in Section 7, which includes recommendations for further work.

[5] A subset of the following; material age, operational environment, material type, total HGV trafficking, HGV trafficking rate, and carriageway type.

[6] Namely; Cumbria, Humberside (Comprising; East Riding, North East Lincolnshire, Hull, and North Lincolnshire), Kent, Norfolk, Nort Yorkshire, Shropshire, and Sommerset.

2 Parameters for road surface condition

2.1 The reported parameters

The condition of road surfaces (or 'pavements') is assessed through the collection of data by survey vehicles. The data is reported using parameters that numerically describe specific attributes of pavement condition. The condition parameters assessed as part of this work are summarised in Table 2-1.

Table 2-1 Condition parameters assessed

<table>
<tr><th>Attribute</th><th>Condition parameters</th><th>Authorities reporting parameter</th><th>Notes</th></tr>
<tr><td rowspan="2">Ride quality</td><td>3m and 10m enhanced Longitudinal Profile Variance (eLPV)</td><td>NH, WG, and TS</td><td rowspan="2">The shape of the road is measured along its length (the longitudinal profile) using lasers mounted on a survey vehicle. The parameters quantify the extent of unevenness in this profile. In the UK there are two parameters (eLPV) that relate to short wave unevenness and long wave unevenness. These are broadly combined in the IRI parameter. Higher parameter values relate to poor ride quality experienced by the user.</td></tr>
<tr><td>International Roughness Index (IRI)</td><td>RWS</td></tr>
<tr><td>Rutting</td><td>Maximum rut depth</td><td>All</td><td>The transverse shape is measured using a laser. Rutting is calculated as the maximum distance between the measured profile and a simulated straight edge in each wheel path. High levels of rutting can affect vehicle stability, result in splash and spray, and can be associated with deterioration in the pavement structure.</td></tr>
<tr><td rowspan="2">Texture depth</td><td>Sensor Measured Texture Depth (SMTD)</td><td>NH, WG, and TS</td><td rowspan="2">Texture depth describes the profile of the surface on the millimetre scale (i.e. due to the shape of the aggregate chips). Texture assists in removing water at the tyre/surface interface and aids in the generation of skid resistance at high speeds. Higher levels of texture depth are generally desirable.</td></tr>
<tr><td>Mean Profile Depth (MTD)</td><td>RWS</td></tr>
<tr><td rowspan="3">Skid resistance</td><td>Characteristic Skid Coefficient (CSC)</td><td>NH</td><td rowspan="3">Road / tyre friction describes the frictional forces generated between a tyre and road surface. Skid resistance is a characterisation of the road surface contribution to tyre road friction. It is measured by moving a tyre along the road such that is slips relative to the driven speed. A lower parameter value is associated with lower levels of skid resistance.</td></tr>
<tr><td>Mean Summer Skid Coefficient (MSSC)</td><td>WG, and TS</td></tr>
<tr><td>SideWay Force (SWF)</td><td>RWS</td></tr>
<tr><td>Cracking and Fretting</td><td colspan="2">It was not possible to gather comparable cracking and fretting data for all of the road authorities – see text.</td><td>Cracking is measured using high speed imaging systems. Cracking is undesirable as it allows water ingress into the lower layers of the road surface which can cause structural defects.

Fretting describes the amount of stone loss from the road surface. High levels of fretting are undesirable as this can affect vehicle stability, tyre noise generation, and friction.</td></tr>
</table>

In this study it was not possible to compare all of the condition parameters across all of the different networks. This is either because the parameters are not collected by all authorities or because different parameters for the same attributes are used by different authorities. For some attributes it was necessary to derive a set of comparator condition parameters to enable the comparison. The parameters considered are summarised in Table 2-2 and discussed further in Appendix B.

Table 2-2 Condition parameters where differences in approach exist between authorities and selection of a "derived parameter" (the prefix 'p' indicates derived parameter)

Attribute	NRAs and Characterisations	Derived parameter	Notes
Rutting	All provide a measure of rut depth in two wheelpaths.	Maximum rut	NH use "max rut" (maximum of the rutting measured in the two wheelpaths) for network assessment. Therefore a max rut value was derived for each authority
Ride quality	**NH:** 3m, 10m and 30m eLPV **WG & TS:** 3m and 10m eLPV **RWS:** IRI	pIRI	It is not possible to directly compare ride quality with RWS without obtaining a derived, comparable, parameter. IRI can be estimated using 3m and 10m eLPV data. Therefore, pIRI was obtained (see Appendix B).
Texture depth	**NH, WG & TS:** SMTD **RWS:** MPD	pSMTD	It is not possible to directly compare texture depth with RWS. MPD can be predicted using SMTD . Therefore, pSMTD was obtained (See Appendix B).
Skid resistance	**NH:** CSC **WG & TS:** MSSC **RWS:** SWF	pSC	CSC is skid resistance corrected for within year and between year variability. MSSC is skid resistance corrected for within year variability only. For this work CSC and MSSC could be compared directly. It is possible to estimate the SC value (uncorrected CSC values) using SWF measurements (See Appendix B). But it should be noted that SC and CSC are not necessarily directly comparable, nor is the conversation between SWF and SC 100% accurate.

Attribute	NRAs and Characterisations	Derived parameter	Notes
Cracking and Fretting	Although cracking data are collected using broadly similar approaches on the UK national and local networks there are substantial differences between the way the data are delivered. On the strategic road network there is evidence that the measurement system has a higher level of sensitivity to cracking than the other UK networks. This could influence comparisons between the network level reporting of cracking on the National Highways and other UK national networks - see Appendix B. For the Netherlands it was not possible to obtain cracking and fretting data as these are characterised using parameters which are directly comparable to the UK measures – see Appendix B. Fretting is not reported routinely on local authority road networks.		

2.2 In-service requirements

The national benchmarking exercise included an assessment of the condition of each network in relation to the in-service requirements currently employed by each authority. The purpose of including this exercise was to understand the effect of in-service requirements on the condition of the networks.

Each road authority has rules or guidance for how condition levels inform maintenance decisions. The requirements for the UK authorities are summarised in CS 230 (Highways England, Transport Scotland, Welsh Government, Department for Infrastructure, 2020) and the requirements for the RWS network are presented in RWS Informatie – Schadenbeoodeling (RWS, 2019).

All of the participating road authorities follow a system of categorisation whereby a condition category is assigned based on a set of requirements. These requirements are set by each road authority (or overseeing organisation) and may therefore differ between road authorities. Therefore, networks performing to the same condition category may have to achieve different requirements to meet that condition category.

Note that, for the purposes of benchmarking, the in service requirements have been based on the “engineering” guidance provided to those maintaining the asset, and not the levels used for the reporting of aggregate condition indices (such as National Highways’ Pavement Condition KPI) for these networks (although there may be cases where the thresholds are similar).

For NH and the WG, four categories are used for the assessment of pavement condition. These categories are summarised in Table 2-3. It is understood that, broadly speaking, areas falling within categories 3 and 4 will be considered for maintenance, with priority being given to those areas with the most severe deterioration. With that in mind, the threshold for condition category 3 was used when considering the in-service requirements for NH and the WG.

Transport Scotland use a three-tier system (Table 2-4). It is understood that broadly speaking areas falling within Amber and Red categories will be considered for maintenance. The threshold for the Amber condition category was used in the assessment of in service requirements for TS.

Table 2-3 NH and WG condition categories for texture depth, rut depth, and eLPV

Condition category	Definition
1	Sound – negligible deterioration
2	Some deterioration – low level of concern
3	Moderate deterioration – warning level of concern
4	Severe deterioration – intervention level of concern

Table 2-4 TS condition categories for texture depth, rut depth, and LPV

Condition category	Definition
Green	Sound – negligible deterioration
Amber	Some to moderate deterioration
Red	Moderate to severe deterioration

The exception to the above is the skid resistance attribute which uses a system of site categorisation (segmenting the network into locations of different properties such as motorways, approaches to junctions, roundabouts, etc…) and the application of an investigatory level (the skid resistance level below which an investigation is carried out into the risk to motorists and appropriate remedial actions) to each site category. In this way the investigatory level for any given section can be used as the in-service requirement.

Similarly to NH and the WG, RWS use a four tier condition category (Ernstklasse) system which categorises each section of road with a numeral I – IV where I represents the best condition and IV the poorest. It is understood that RWS seek to maintain their network to Ernstklasse III. Hence the thresholds for this level were applied in the analysis.

For the assessment of cracking and fretting, guidance is provided on the interpretation of measurements made using TRACS devices in CS 230 (Highways England, Transport Scotland, Welsh Government, Department for Infrastructure, 2020), and in the HAPMS documentation (Highways England (National Highways), 2019). These documents refer to the assessment of TRACS data. The thresholds cannot be applied to cracking data obtained from the WG and TS networks as they categorise cracking using SCANNER devices. For this reason cracking and fretting in-service requirements were not used in the analysis.

A summary of the in-service requirements specified for each of the networks is provided in Table 2-5. It can be noted from Table 2-5 that:

- NH and the WG have adopted the same in-service requirements for all parameters.
- RWS have adopted more strict requirements for ride quality (IRI) than NH/WG.
- TS have stricter rutting requirements than NH/WG whereas RWS have adopted slightly more relaxed requirements.
- All of the UK networks have the same in-service requirements for texture depth, but RWS does not have an in-service requirement for this attribute. This may be because of the extensive use of porous asphalt in the Netherlands, for which texture may not be the most effective measure of condition.

- The UK networks have the same in-service requirements for skid resistance, based on “site categories”, which indicate the relative skidding risk at each location on the network. RWS has adopted a slightly different approach, assigning different in-service requirements to porous and dense materials measured at different speeds.

Table 2-5 Summary of in-service requirements used in the national benchmarking

<table>
<tr><th>Condition parameter</th><th>Network</th><th>In-service requirement</th></tr>
<tr><td rowspan="4">Ride quality 3m eLPV</td><td>NH</td><td rowspan="2">Motorways and rural dual carriageways: < 4.4
Urban dual carriageways and rural single carriageways : <5.5
Urban single carriageways: <9.3</td></tr>
<tr><td>WG</td></tr>
<tr><td>TS</td><td rowspan="2">N/A</td></tr>
<tr><td>RWS</td></tr>
<tr><td rowspan="4">Ride quality 10m eLPV</td><td>NH</td><td rowspan="2">Motorways and rural dual carriageways: < 14.7
Urban dual carriageways and rural single carriageways : <28.8
Urban single carriageways: <36.6</td></tr>
<tr><td>WG</td></tr>
<tr><td>TS</td><td rowspan="2">N/A</td></tr>
<tr><td>RWS</td></tr>
<tr><td rowspan="4">Ride quality IRI</td><td>NH</td><td rowspan="2">Parameters mirror those for 3m and 10m eLPV but were converted to pIRI. This resulted in the following:
• Motorways and rural dual carriageways: < 7.66
• Urban dual carriageways and rural single carriageways : <9.06
• Urban single carriageways: <11.62</td></tr>
<tr><td>WG</td></tr>
<tr><td>RWS</td><td>Network wide: < 4</td></tr>
<tr><td>TS</td><td>N/A</td></tr>
<tr><td rowspan="4">Rutting</td><td>NH</td><td rowspan="2">Network wide: < 20</td></tr>
<tr><td>WG</td></tr>
<tr><td>TS</td><td>Network wide: < 15</td></tr>
<tr><td>RWS</td><td>Network wide: < 23</td></tr>
<tr><td>Cracking and Fretting</td><td>N/A</td><td>N/A</td></tr>
<tr><td rowspan="4">Texture depth</td><td>NH</td><td rowspan="3">For high friction surfacings: > 0.6
For non-high friction surfacings: >0.4</td></tr>
<tr><td>WG</td></tr>
<tr><td>TS</td></tr>
<tr><td>RWS</td><td>N/A</td></tr>
<tr><td rowspan="4">Skid resistance</td><td>NH</td><td rowspan="3">The difference between measured skid resistance and the in-service requirement was provided in the individual datasets and so parameters were not derived for these networks.</td></tr>
<tr><td>WG</td></tr>
<tr><td>TS</td></tr>
<tr><td>RWS</td><td>In service requirements for the RWS network are as provided in the following table.</td></tr>
</table>

<table>
<tr><th>Condition parameter</th><th>Network</th><th>In-service requirement</th></tr>
<tr><td></td><td></td><td>
<table>
<tr><th>Test speed (km/h)</th><th>Porous materials</th><th>Dense materials</th></tr>
<tr><td>40</td><td>0.57</td><td>0.63</td></tr>
<tr><td>60</td><td>0.54</td><td>0.57</td></tr>
<tr><td>80</td><td>0.51</td><td>0.53</td></tr>
</table>
</td></tr>
</table>

3 National benchmarking

3.1 Parameters for comparison

Table 3-1 summarises the parameters that were compared during the national benchmarking.

Table 3-1 Parameters for national benchmarking

<table>
<tr><th rowspan="2">Attribute</th><th colspan="4">Network</th></tr>
<tr><th>NH</th><th>TS</th><th>WG</th><th>RWS</th></tr>
<tr><td>Texture depth</td><td colspan="3">SMTD (NSWP)</td><td>pSMTD (NSWP)</td></tr>
<tr><td>Skid resistance</td><td colspan="3">CSC</td><td>pCSC</td></tr>
<tr><td rowspan="2">Ride quality</td><td colspan="3">Max eLPV 3m
Max eLPV 10m</td><td>Not assessed</td></tr>
<tr><td colspan="4">IRI (pIRI)</td></tr>
<tr><td>Rutting</td><td colspan="4">Max Rut</td></tr>
<tr><td>Cracking</td><td>Lane cracking</td><td colspan="2">Area cracking</td><td>Years to maintenance</td></tr>
<tr><td>Fretting</td><td>Lane fretting</td><td colspan="2">Not assessed</td><td>Years to maintenance</td></tr>
</table>

3.2 Approach

3.2.1 Distributions

Parameters - Histograms and cumulative frequency distributions. Network level comparisons were made by producing histograms and cumulative frequency distributions of the condition parameters. Histograms of condition parameters were also produced following the segregation of each network by carriageway type; motorway, dual-carriageway, and single-carriageway.

In service requirements - Histograms and cumulative frequency distributions. An assessment was carried out of the influence of the in-service requirements on the condition parameters for each network. This subtracted the condition parameter from the in-service requirement for that parameter for each reported length. Histograms and cumulative frequency distributions of these difference datasets were plotted. For example, Figure 3-1 shows the cumulative frequency distribution of the differences of the 3m eLPV values from the in service requirements. In this plot, all positive values are exceeding the in-service requirement, it can be observed therefore that the vast majority of both the WG and NH networks are exceeding their in-service requirements. The majority of values for both networks is around 4 meaning that at a network level, the WG and NH networks are exceeding their in-service requirements by approximately 4 units (mm^2 for eLPV).

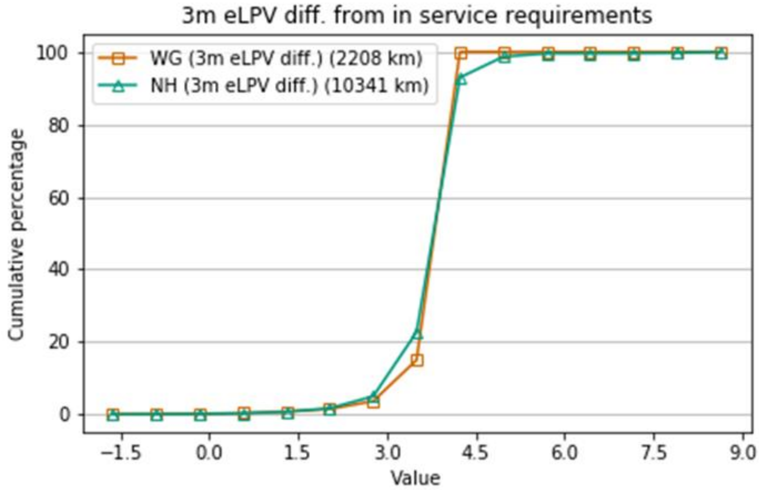


Figure 3-1 Example cumulative frequency distribution of differences from in-service requirements: 3m eLPV

3.2.2 Statistical testing: Cohen's d-test

Cohen's d-tests were carried out for each possible combination of networks to determine the amount of agreement (low effect size) or disagreement (large effect size) between the datasets. The Cohen's d-test[7] was applied as per Equation 1. It compares the differences in the mean values of two distributions with the pooled standard deviation for those distributions. The results of the test are reported on a discrete scale from Negligible (low effect size) to High (large effect size).

$$\frac{|\overline{x_a} - \overline{x_b}|}{\sqrt{\dfrac{(n_a - 1)\sigma_a^2 + (n_b - 1)\sigma_b^2}{n_a + n_b - 2}}}$$

Where:

- $\overline{x_a}$ = The mean value for network 'a'
- n_a = The sample size for network 'a'
- σ_a = The standard deviation for network 'a'

Equation 1 The Cohen's d-test

Note that it is best practice (but not essential) for the Cohen's d-test to be applied to data that are normally distributed[8]. In instances where a dataset does not follow a normal distribution the Cohen's d-test was carried out on a dataset after the natural logarithm had been applied. An example is presented in Figure 3-2. In this figure the distributions of 10m

[7] The Students t-test was considered but this test is inappropriate in this case owing to sample size.

[8] Data that follow the form of a bell curve.

eLPV, on the left, are not normally distributed (it is not possible to have negative eLPV). The graph on the right presents the same data after having applied the natural logarithm. This has had the effect of normally distributing the data (in this case around zero) supporting the application of the Cohen's d-test.

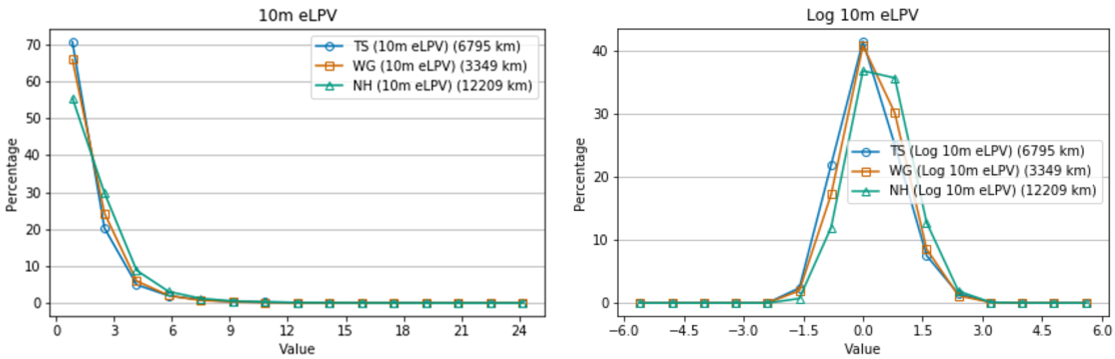


Figure 3-2 Example: distributions of 10m eLPV (left) and Log 10m eLPV (right)

3.2.3 Statistics

The following statistics describing the datasets were calculated:

- Mean
- 95th percentile
- 5th percentile
- Standard deviation
- Skew
- Kurtosis
- Distribution normality (skew and kurtosis were used to derive this statistic)

4 Results of the national benchmarking and selection of parameters for the deeper dive

The results of the national benchmarking were collated as a series of “dashboards” showing all of the comparisons discussed in the section above. These are presented in Appendix D. In this section we discuss the pertinent observations on these results, and the implications for the deeper dive.

4.1 Ride Quality

4.1.1 3m eLPV

The results of the national benchmarking for 3m eLPV presented in Figure 4-1 suggest that the UK networks have similar levels of 3m eLPV. When comparing the NH with the TS and WG networks a small amount of disagreement is observed but this was not identified in the statistical testing. The assessment of in-service requirements suggest that a substantial percentage of both the NH and WG networks exceed (i.e. are better than) the condition thresholds selected for the in-service comparison. Both networks show a similar proportion of the network exceeding the requirements. It is noteworthy that the in-service requirements for the NH and WG networks are the same. When this assessment was broken down by carriageway type the results largely mirrored the results of the network assessment. For motorways, some divergence was seen between the TS and WG networks, but this was of a negligible magnitude.

Given the amount of agreement between the networks, 3m eLPV was **not recommended** for the deeper dive.

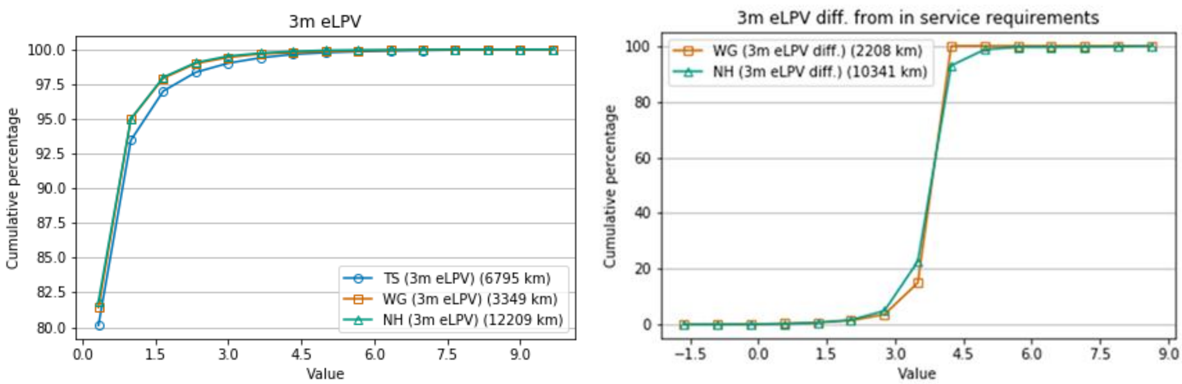


Figure 4-1 Cumulative frequency distribution of 3m eLPV values, and distribution of 3m eLPV difference from in-service requirements

4.1.2 10m eLPV

The results for 10m eLPV largely reflected those seen for 3m eLPV. The assessment of in-service requirements showed negligible disagreement between the NH and WG networks and breaking the assessment down by carriageway type largely mirrored the results of the network level assessment. However, for non-motorways the NH distribution was shifted to the right of the WG and TS networks, suggesting that these roads are slightly rougher on the NH network.

Given the amount of agreement between the networks, 10m eLPV was **not recommended** for the deeper dive.

4.1.3 IRI

For the UK networks IRI was assessed using pIRI (estimate of IRI obtained using 3m and 10m eLPV). Figure 4-2 shows that the UK networks are providing similar levels of pIRI, a finding that is not surprising given the agreement observed for 3m and 10m eLPV above. However, the RWS network provides substantially lower levels of IRI than the UK networks, an observation that was borne out in the results of the Cohen's d-test. The assessment of carriageway type largely mirrored the results of the network level assessment.

The observations suggest that the RWS network is, on the whole, a smoother network. The assessment of in-service requirements mirrored the behaviour observed from the parameter distributions. As shown in Table 2-5, RWS have higher in-service requirement for smoothness than the UK networks. The high levels of smoothness on the RWS network may be being driven by these stricter requirements.

IRI was recommended for inclusion in the deeper dive to explain the difference observed between the RWS and UK road networks.

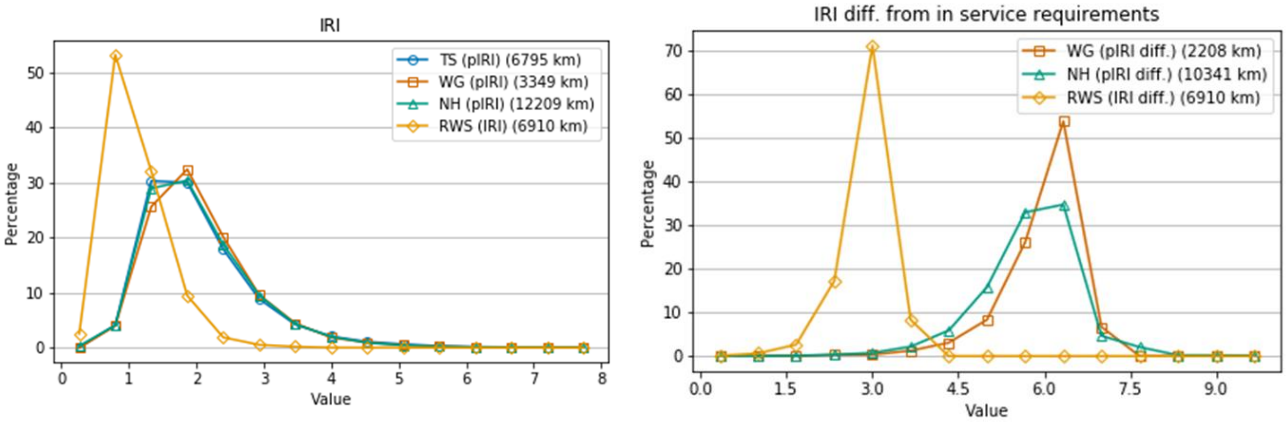


Figure 4-2 Histogram of IRI values, and difference from in-service requirements[9]

4.2 Rutting

Figure 4-3 shows similarities between the RWS and NH networks, and the WG and TS networks. However, substantial differences were observed between the RWS/NH and WG/TS networks. The RWS/NH networks have large amounts of skew (large tails on one side

[9] Note: TS have no in-service requirements for eLPV (the parameter used to derive IRI) and so do not appear in the difference from in-service requirements chart.

of the distribution), and the WG/TS networks have comparatively small amounts of skew. For the in-service requirements a similar behaviour to that seen for IRI is noted:

- All networks are exceeding their in-service requirements, and
- the in-service requirements do not appear strongly correlated to the condition data, i.e. all networks are markedly exceeding the requirements.

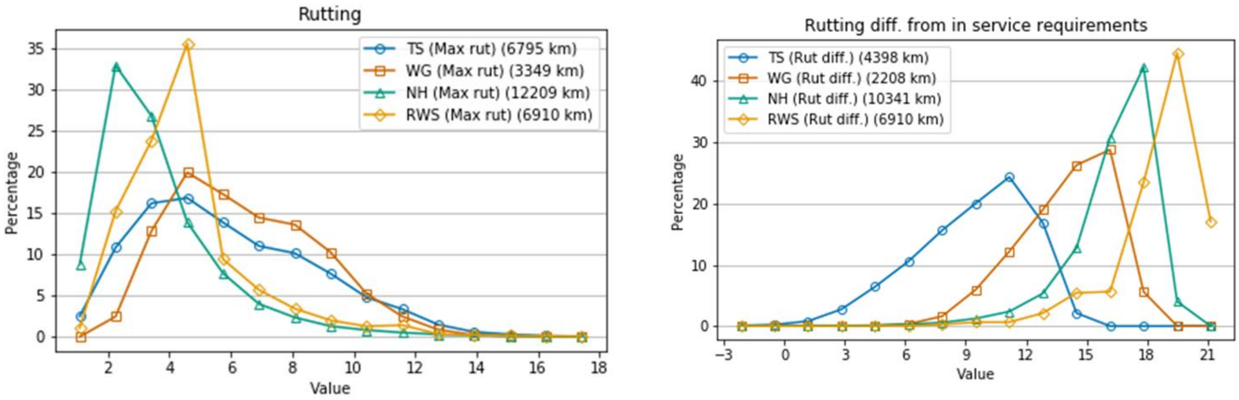


Figure 4-3 Histogram of rutting values, and differences from in service requirements

Consideration of carriageway type (Figure 4-4) goes some way to reducing the differences observed in the network level assessments. This is particularly the case for motorways and dual carriageways, which demonstrated the largest amount of agreement between sub-networks. An assessment of carriageway type could therefore offer insight as part of future work.

Given the difference in condition of the RWS/NH and WG/TS networks, Rutting was **recommended** for the deeper dive.

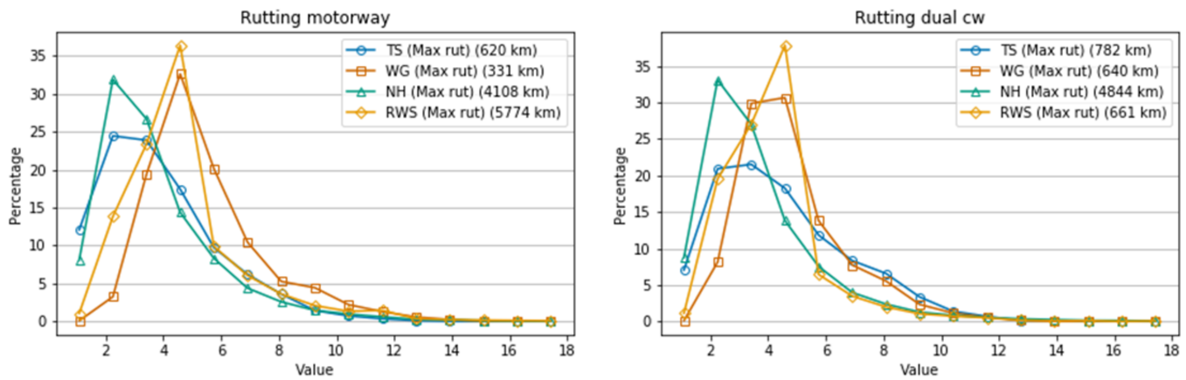


Figure 4-4 Histograms of rutting values for motorways (left) and dual carriageways (right)

4.3 Cracking

The results of Figure 4-5 demonstrate a negligible difference in the condition of the TS and WG networks, but large differences between these networks and the NH network. The cracking data from the RWS network are not comparable with the UK networks, they have been included in Figure 4-5 for reference but were not considered during the analysis. The assessment of carriageway type largely mirrored the results of the network level assessment.

Given the amount of disagreement between NH and WG/TS networks, Cracking was **recommended** for the deeper dive.

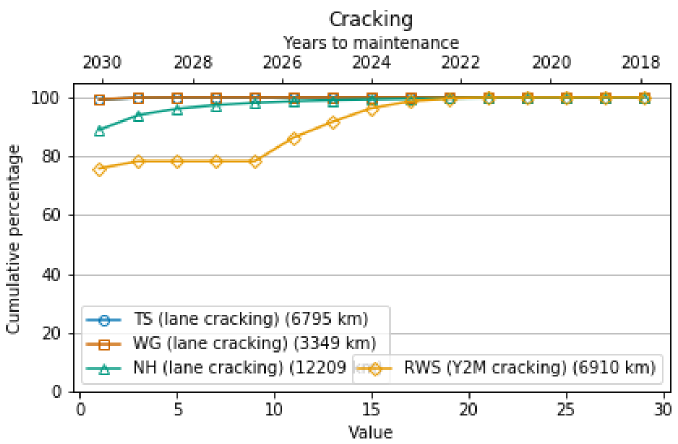


Figure 4-5 Cumulative frequency distribution for cracking values

4.4 Fretting

Fretting data were not available for the national benchmarking exercise for the WG and TS networks. Furthermore, the fretting data from the NH network was not comparable with the RWS data as they use very different parameters to measure fretting. For this reason it was **not possible** to consider Fretting for the deeper dive.

4.5 Texture depth

Figure 4-6 suggests that the UK networks are providing similar levels of texture depth. Differences were observed between the UK networks and RWS network, these differences being driven by a greater skew and small amount of bi-modality (the presence of two peaks, one at ~0.5mm and the other at ~0.9mm). The assessment of in-service requirements mirrored those of the overall condition parameter assessment. This is unsurprising given the similarity in in-service requirements for the networks (Table 2-5).

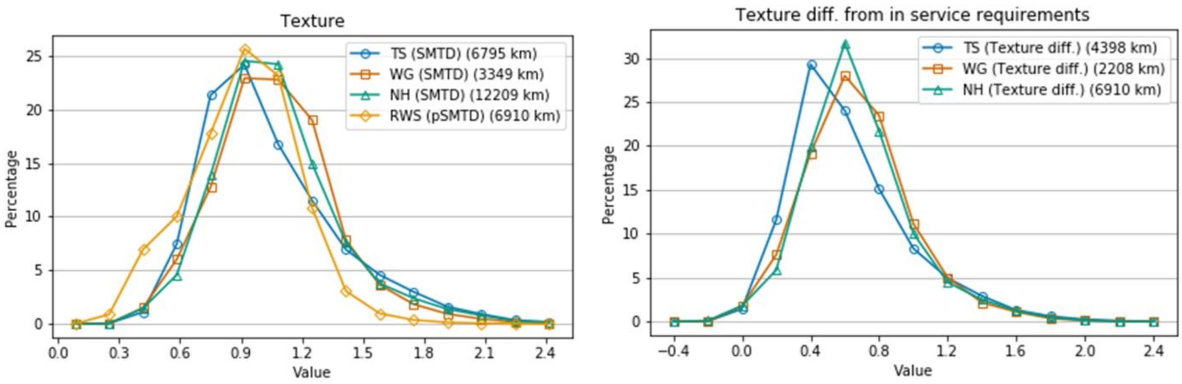


Figure 4-6 Histogram of texture depth values, and differences from in service requirements

For texture there were some differences observed when the networks were broken down by carriageway type:

- For motorways, the condition of the RWS network was largely similar to that observed at a network level. This observation is however expected given that approximately 77% of the RWS network is comprised of motorway sections.
- For dual-carriageways (Figure 4-7 (left)), the condition of the RWS network shows differences to the overall network level assessment, namely an increase in skew and the 'second peak' are observed.
- For single-carriageways (Figure 4-7 (right)), the RWS data clearly demonstrated bi-modality with the 'second peak' becoming larger than the 'main peak'.

To examine the differences identified from the network level study, texture depth was **recommended** for the deeper dive.

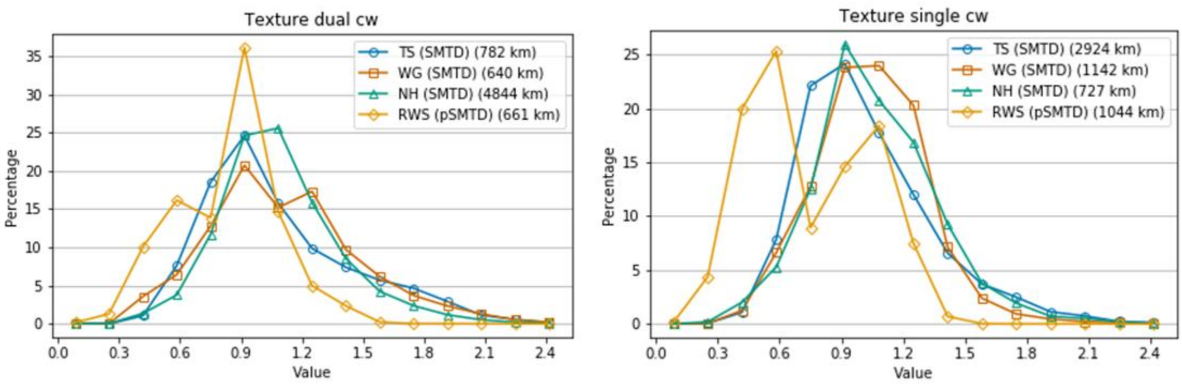


Figure 4-7 Histograms of texture depth values for dual carriageways (left) and single carriageways (right)

4.6 Skid resistance

The national benchmarking results for skid resistance (Figure 4-8 left) showed varied condition between the networks. The RWS and WG networks are providing the largest average skid resistance levels, and the NH network provides the lowest average skid resistance. However, when the in-service requirements are taken into account (Table 2-5) the distributions of differences from the UK networks (Figure 4-8 right) broadly align, with small or negligible differences observed between the UK networks.

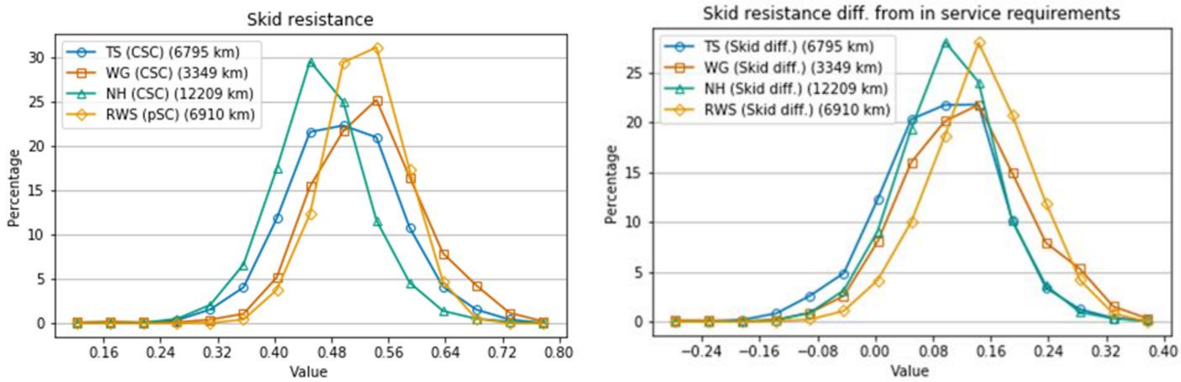


Figure 4-8 Histogram of skid resistance values and difference from in-service requirements

It is notable that for IRI and rutting, the assessment of in-service requirements did not result in the same level of alignment between the UK networks as was the case for skid resistance. This suggests that on the UK networks, skid resistance is managed in a different way to ride quality (IRI) and Rutting, and that this difference results in the skid resistance in-service requirement having a greater influence on skid resistance performance than the ride quality and rutting in-service requirements do on those attributes. This is discussed further in Chapter 7.

The assessment of carriageway type for single carriageways largely mirrored the results of the network level assessment. For motorways (Figure 4-9 (left)) and dual carriageways (Figure 4-9 (right)), a greater level of agreement between the TS and NH networks was observed, whereas the condition of the WG and RWS networks diverged.

To examine the differences in network condition outlined above, skid resistance was **recommended** for the deeper dive.

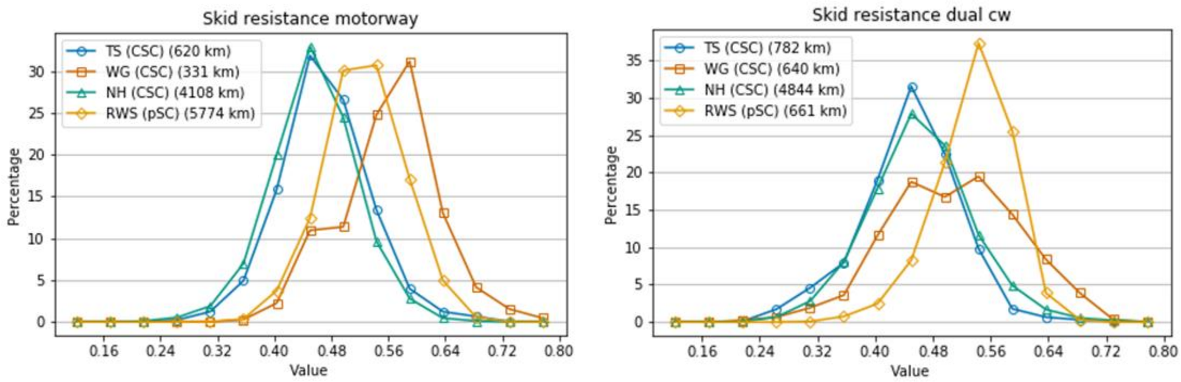


Figure 4-9 Histograms of skid resistance values for motorways (left) and dual carriageways (right)

5 The deeper dive

5.1 Approach

The deeper dive analysis sought to explain any differences in network condition identified in the national benchmarking through the analysis of additional explanatory variables. Drawing on the recommendations of the network assessment above, the following combinations of condition parameters, and additional explanatory variables were assessed:

- ride quality (IRI); assessed by material type and total trafficking,
- rutting; assessed by age, material type and total trafficking,
- cracking; assessed by age, material type and total trafficking,
- texture depth; assessed by age, material type and total trafficking, and
- skid resistance; assessed by age, material type and trafficking rate.

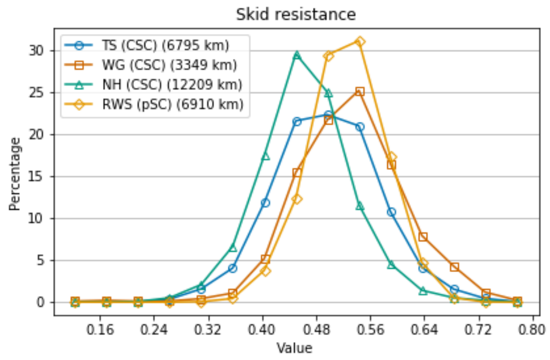
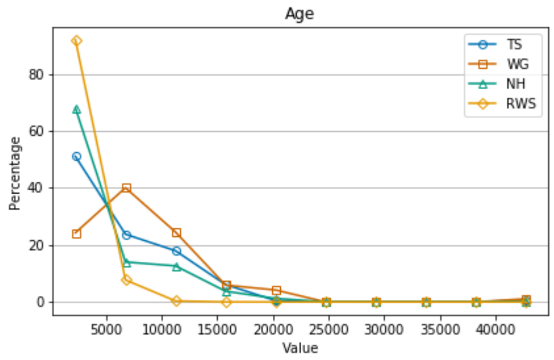
The method used to select the explanatory variables is provided in Appendix F, and the sources of data used for the explanatory variables are provided in Appendix A.

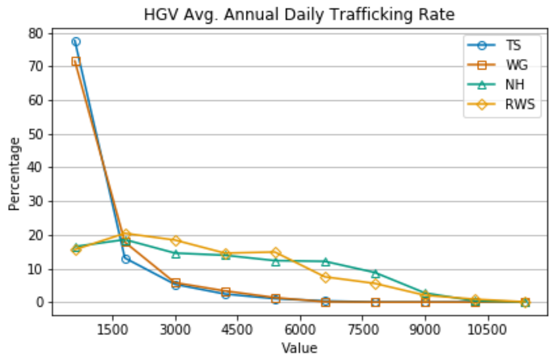
The deeper dive was split into three stages:

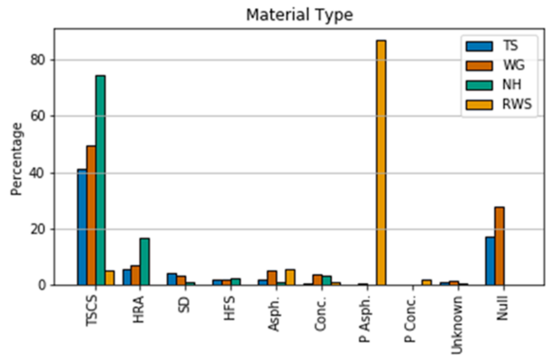
1. Additional parameter selection
2. Data processing and analysis
3. Draw conclusions

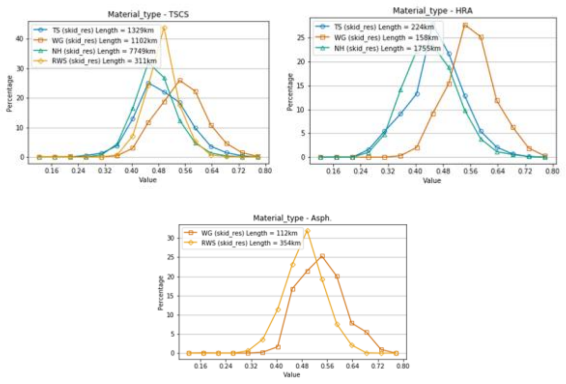
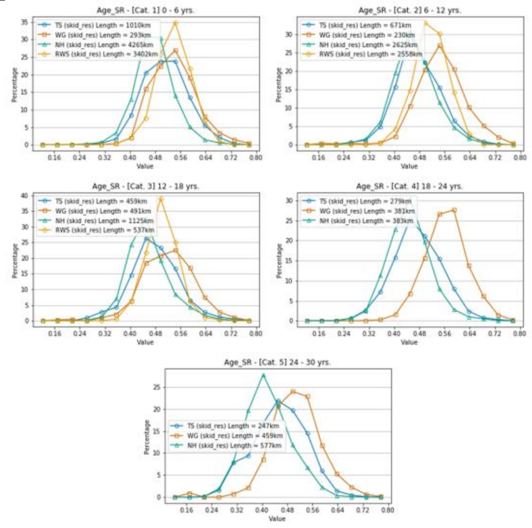
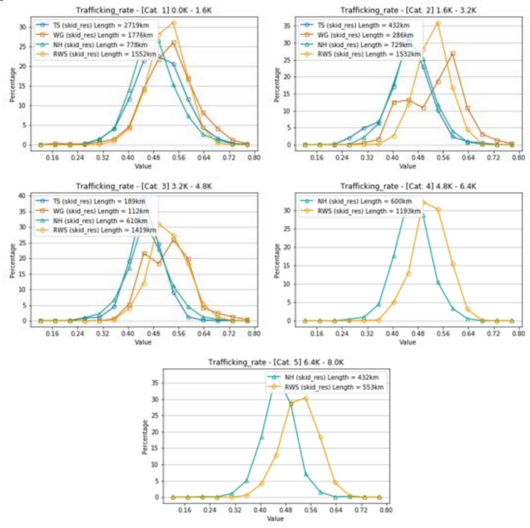
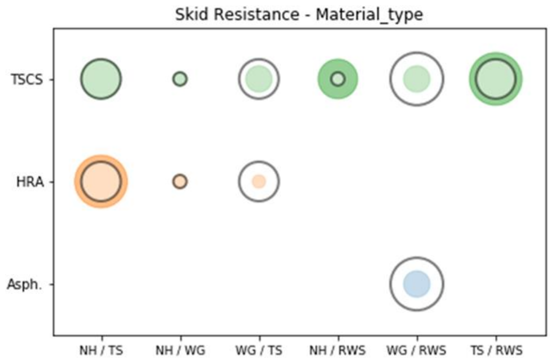
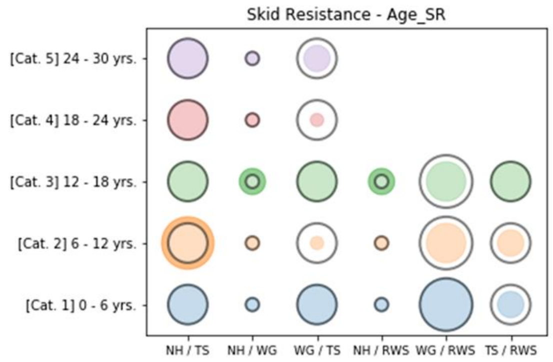
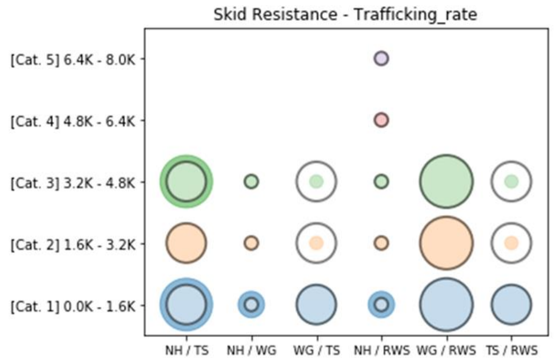
The process of moving from the national benchmarking to the deeper dive is presented below in Table 5-1 using skid resistance as an example. Further information is provided in Appendix F.

Table 5-1 Approach to the deeper dive – example for skid resistance

<table>
<tr><td colspan="3">Stage 0: Perform the national benchmarking and identify condition parameters that should be assessed as part of the deeper dive:</td></tr>
<tr><td colspan="3">
</td></tr>
<tr><td colspan="3">Stage 1.1: Selection of additional explanatory variables, assess the distribution of additional explanatory variables.</td></tr>
<tr><td colspan="3">





etc…</td></tr>
<tr><td colspan="3">Stage 1.2: Identify the additional explanatory variables that could have the most explanatory power, split the data by those categories and produce histograms and CFDs.</td></tr>
<tr><td>Material type</td><td>Age</td><td>Trafficking rate</td></tr>
<tr><td></td><td></td><td></td></tr>
<tr><td colspan="3">Stage2: Perform a Cohen's d-test on the split data and produce bubble plots (see Appendix F for an explanation of bubble plots).</td></tr>
<tr><td>
</td><td>
</td><td>
</td></tr>
<tr><td colspan="3">Stage 3: Assessment of explanatory power</td></tr>
<tr><td>Not explained</td><td>Not explained</td><td>Partly explains</td></tr>
</table>

5.2 Results of the deeper dive

The full set of results of the deeper dive are provided in Appendix G. This section provides a summary of these results in **Table 5-2**, which presents the observations made, provides the assessment of explanatory power, and the recommendations made.

Table 5-2 Summary results from the deeper dive

Parameter and explanatory variable	Observations	Explanatory power	Recommendations
Ride quality (IRI) - Material type	The results from Thin Surface Coarse Systems (TSCSs) mirror the results of the national benchmarking. The results from Hot Rolled Asphalts (HRAs) demonstrate a larger difference between the condition of the UK networks than was observed during the national benchmarking.	Not explained.	An assessment of material type below the surface layer could offer additional insight into the effect of materials on IRI. For example, it is anticipated that asphalt surfaces laid on a concrete base should be less susceptible to changes in longitudinal profile than materials laid on an asphalt base.
Ride quality (IRI) - Total trafficking	The results from all categories largely mirror those from the national benchmarking but with a lower amount of agreement between the UK networks. Assessing IRI based on the total trafficking received does not explain the differences in network condition.	Not explained.	None.
Ride quality (IRI) - Overall recommendations Based on the data presented here future analyses should include an assessment of material types at all layers of construction.			
Rutting - Age	For road surfaces aged between 0 and 12 years the differences shown in the national benchmarking are somewhat reduced but there still exists a substantial difference between the performance of the networks, this is particularly apparent for the TS / RWS comparison. Above 12 years, a much closer behaviour between networks is observed. It is clear therefore that an assessment of age can partly explain the differences between the differences in rutting between networks observed in the national benchmarking exercise.	Partly explains.	None.

Parameter and explanatory variable	Observations	Explanatory power	Recommendations
Rutting - Material type	For TSCS surfaces the patterns observed in the national benchmarking data were largely replicated. The condition of the RWS network however was more similar to the TS network, leading to a reduction in disagreement between these networks. For HRA surfaces, differences between the UK networks were smaller than for the national benchmarking. Small differences between the TS and NH/WG networks were observed, and a medium difference between the NH and WG networks was observed.	Partly explains.	Material type appears to partly explain the differences in rutting shown in the national benchmarking. As with the assessment of IRI it is anticipated that materials at all construction levels could influence the prevalence of rutting. It is therefore recommended that future analyses include an assessment of material type at all construction layers.
Rutting - Total trafficking	In comparing the NH network with the comparators, it was observed that segregation by total trafficking offers little explanation of the differences observed in the national benchmarking. For the RWS network, the relationships with the WG and TS networks (as determined through the Cohen's d-test) improve markedly after the surface is exposed to 4 million HGVs. The histograms indicate that this improvement is driven by two factors: 1. A change in the shape of the WG distribution (to conform more to the shape of the RWS distribution); and 2. The shifting of the RWS peak to the right of the distribution with increasing total trafficking. The explanatory power of the total trafficking appears, on the whole, lower than that for material age. But does offer some valuable insight regarding the condition of the RWS network.	Partly explains.	Given the relationships observed in the deeper dive between rutting and, age and material type it is recommended that future analyses be carried out by splitting material type by age.

Parameter and explanatory variable	Observations	Explanatory power	Recommendations
Rutting - Overall recommendations Based on the data presented here, future analyses should include an assessment of material types at all layers of construction. An additional variable that was not available for assessment during this work was pavement temperature. It is anticipated that for asphalt materials, exposure to high temperatures could make the bitumen more malleable than materials in colder climes. Future analysis may therefore benefit from an assessment of environmental effects. Future analyses may also gain insight from a more granular assessment of material type (for asphalt materials), for example; the grading of the aggregate, the type and properties of the bitumen used, the use of bitumen additives (e.g. polymer modification), and the characteristics of the materials / environment during laying.			
Cracking - Age	For all ages, the relationship between the WG and TS networks were similar for all categories. An interesting behaviour is observed in the NH data which shows that cracking increases with age. Between 0 and 6 years, lower cracking values account for approximately 95% of the data, whereas between 24 and 30 years this percentage decreases to approximately 55%. The data suggest material age does not provide an explanation for the observed differences in cracking between the networks.	Not explained.	None.
Cracking - Material type	For TSCS and HRA surfaces the same amount of disagreement between the networks is observed. Comparing the cumulative frequency distributions for HRA surfaces, it appears to be the case that greater amounts of cracking are observed on HRAs than TSCSs. It may be the case that this observation is inter-related with age as HRAs (at least on the NH network) are seldom used in newer works. It is noted that the overall cracking condition of TSCS materials align with the overall cracking condition of TSCSs between 0 and 12 years, whereas the overall condition of HRAs align with HRAs between 24 and 30 years. The data suggest material type does not provide an explanation for the observed differences in cracking between the networks.	Not explained.	Further insight may be gained by further splitting material type by age and assessing the relationships between material type and material age.

<table>
<tr><th>Parameter and explanatory variable</th><th>Observations</th><th>Explanatory power</th><th>Recommendations</th></tr>
<tr><td>Cracking - Total trafficking</td><td>In comparing the condition of the NH network to the other networks, the amount of agreement between the networks seems to increase.
This is particularly evident when comparting the NH network to the WG network where a small amount of disagreement was observed between 12 and 20 Million HGVs.</td><td>Partly explains.</td><td>It has been shown that there appears to be a correlation between material age and cracking for the NH network. Total trafficking necessarily includes material age in its derivation. Further insight could therefore be gained by understanding the effect of trafficking rate on cracking prevalence.</td></tr>
<tr><td colspan="4">Cracking - Overall recommendations
The following recommendations are made regarding future assessment of cracking:
• Whilst none of the parameters assessed here could fully explain the differences in network condition observed during the national benchmarking, the inter-dependency of these parameters be assessed through more sophisticated statistical means (Machine Learning or AI).
• The effect of environmental features on the prevalence of cracking be assessed. For example, it is anticipated that exposure to UV light can have a ‘stiffening’ effect on bituminous materials.
• The relationship between cracking and trafficking rate should be assessed for materials of similar types and ages.
• NH uses TRACS to characterise cracking whereas the WG and TS use SCANNER. Whilst both methodologies use similar measurement technologies, the algorithms used to process the data differ fairly substantially.
It is hypothesised that the differences in cracking observed in the national benchmarking are related to the methodologies used to characterise cracking. To test this hypothesis future work could:
• Investigate the differences in characterisation methodologies in order to produce a correction factor between TRACS and SCANNER, and/or;
• Complete TRACS surveys on the WG and TS networks to allow for a like-for-like comparison of cracking.</td></tr>
<tr><td>Texture depth - Age</td><td>For all but ages between 6 and 18 years, the difference in condition between the NRAs diverged, on the whole, from the national benchmarking. Between 6 and 12 years, a slightly better agreement is observed on the whole.
The data presented demonstrate suggest that material age does not provide a strong explanation for the observed differences in texture depth between the networks.</td><td>Not explained.</td><td>None.</td></tr>
</table>

Parameter and explanatory variable	Observations	Explanatory power	Recommendations
Texture depth - Material type	Whilst some networks demonstrated the same amount of agreement with the national benchmarking exercise, on the whole, splitting the analysis by material type has resulted in a poorer agreement between networks. The data presented demonstrate suggest that material type does not provide a strong explanation for the observed differences in texture depth between the networks.	Not explained.	None.
Texture depth - Total trafficking	Whilst some networks demonstrated a greater amount of agreement with the national benchmarking, on the whole, splitting the analysis by total trafficking has resulted in a similar agreement between networks. The data presented here demonstrate suggest that total trafficking does not provide a strong explanation for the observed differences in texture depth between the networks.	Not explained.	None.
Texture depth - Overall recommendations No specific recommendations regarding texture depth were made as part of the deeper dive. However a more granular assessment of material type on texture depth could be carried out. It is generally accepted that the specific formulation of road materials can have a substantial effect on their texture depth. For example, TSCS materials may have nominal aggregate sizes ranging between 6mm and 20mm.			
Skid resistance - Age	For all ages the level of agreement between the networks was, on the whole, similar to that observed in the national benchmarking. Whilst some combinations of ages and networks provided better agreement than that observed in the national benchmarking, this was not consistent enough to provide any explanatory power. This finding is particularly interesting given that the RWS network demonstrated a substantially different distribution of material ages in comparison to the UK networks. It is also noted that the RWS network is primarily comprised of porous asphalt materials which may have different ages to other material types.	Not explained.	None.

Parameter and explanatory variable	Observations	Explanatory power	Recommendations
Skid resistance - Material type	When splitting the national benchmarking data by material type, the level of agreement between the networks was, on the whole, similar to that observed in the national benchmarking. Whilst some materials and networks provided better agreement than that observed in the national benchmarking, this was not consistent enough to provide any explanatory power.	Not explained.	The material type with the most explanatory power is TSCSs. Previous research ((Roe & Lagarde-Forest, 2005), (Greene & Crinson, 2008), (Greene, Sanders, & Roe, 2010)) has shown that the skid resistance of TSCSs materials can change markedly[10] in the weeks and months after installation. It is recommended that future analyses assess the inter-dependency between material type and age to determine the explanatory power of their combined effects.
Skid resistance - Trafficking rate	In splitting the skid resistance data by trafficking rate, the overall agreement between the networks is lower than that observed in the national benchmarking. The key exception to this is that generally better agreements between the networks were observed on roads with the lowest trafficking rates.	Partly explains	The observations made here support the hypothesis that there is an interplay between material type and age as trafficking rate is a factor in this relationship.
Skid resistance - Overall recommendations Future analyses, building on the work of (Roe & Lagarde-Forest, 2005), (Greene & Crinson, 2008), and (Greene, Sanders, & Roe, 2010), could include an assessment of the inter-related effects of material type, material age, and trafficking rate. Future analyses could also split the data by the in-service requirements of the networks.			

[10] This is typified by an increase in skid resistance as the bitumen layer on the aggregate is worn by weathering and trafficking, followed by a reduction in skid resistance to an equilibrium level which remains relatively stable for the remainder of the service life of the material.

6 Comparison with Local Authorities

6.1 Local Authority networks and approach to analysis

The Local Authority (LA) comparison was carried out using the same parameters used in the national benchmarking (see Section 1). The LA networks used in the analysis are listed below. Local Authority comparisons were carried out using the Principal Local Road Networks (i.e. typically the A road networks maintained by each local Highway Authority). In addition to “national” comparisons in which the entire LA dataset was combined for comparison with the national networks, the LA data from individual authorities was also compared to the National Highways data, but only for those sections of the National Highways network (i.e., the National Highways sub-network) that lay within the local authority boundaries for each local authority. The assessment was carried out using the same process as described in Section 3.2.

SCRIM and SCANNER Data:

- East Riding (Humberside)
- Norfolk
- North East Lincolnshire (Humberside)

SCANNER Data:

- Cumbria
- Hull (Humberside)
- Kent
- North Lincolnshire (Humberside)
- North Yorkshire
- Shropshire
- Somerset
- Suffolk
- Surrey

6.2 Results

As for the national benchmarking, the results of the local authority benchmarking were collated as a series of “dashboards”. These are presented in Appendix I. In this section the pertinent observations based on the results are presented.

6.2.1 Ride quality (3m and 10m eLPV)

At the “network level”, the LA networks typically provide higher levels of 3m eLPV to (i.e. are rougher than) the national networks. Comparison of individual LAs with the corresponding locations on the National Highways network showed similar results to the network level comparison. Humberside and Norfolk were interesting exceptions to this, where the distributions were broadly similar (i.e. they have similar levels of ride quality) to the National Highways network. The 10m eLPV results were broadly similar to the 3m eLPV results, with the exception that the Norfolk and Humberside LA networks demonstrate less agreement with the National Highways network.

6.2.2 Rutting

The LA networks have higher levels of rutting than the NH. The shapes of the distribution were closer to that of the TS/WG networks than to that of the NH/NL networks. These observations were largely mirrored when the LA networks were compared with their National Highways sub-networks.

6.2.3 Cracking

The network level comparison of cracking reported on the LA and national networks showed that the cracking distributions on the LA networks agrees well with the distributions on the TS and WG networks, but agreed poorly when compared with the NH network – for which higher levels of cracking were reported. Cracking on the LA networks is determined using SCANNER surveys, whereas the NH network is assessed using TRACS. As discussed above, it is suspected that the increased sensitivity of the TRACS survey is driving this difference.

The results from individual LA networks typically mirrored those of the corresponding National Highways sub-networks. Interestingly, this was not the case for Norfolk, for which the National Highways network reported a lower level of cracking.

6.2.4 Texture depth

The network comparison (**Figure 6-1**) suggested that, overall, the LA networks are providing much lower levels of texture than the national networks. This was broadly mirrored when the LA networks were compared individually, but there were some exceptions; Surrey, Cumbria and Sommerset showed much closer agreement with the corresponding National Highways sub-networks. A further observation made in the assessment of the sub-networks was that some (Norfolk, Shropshire, and Suffolk) demonstrate a level of bi-modality in the NH distributions (Figure 6-1, right). It is hypothesised that this arises from the presence of different material types on these sub-networks. It is known that concrete materials offer lower levels of texture depth than asphalt materials. A sub-network for which there are significant lengths of both concrete and asphalt materials could therefore induce bi-modality in the distributions.

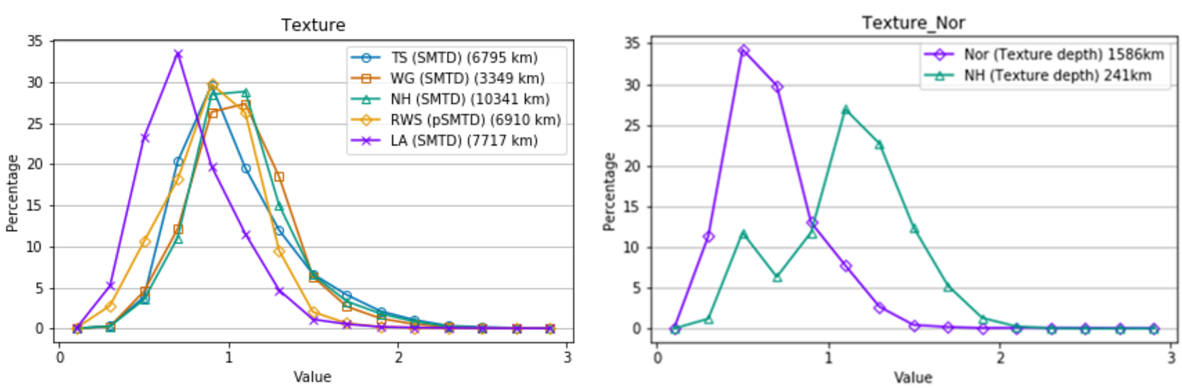


Figure 6-1 Whole network results for the local authority comparison for texture depth (left) and comparing Norfolk and NH (right)

6.2.5 Skid resistance

The whole network assessment of skid resistance showed that, overall, the LA networks (for which skid resistance data was available) provide lower levels of skid resistance than the national networks. The comparison of the LAs with their corresponding National Highways sub-networks was less conclusive. For example, the results from Humberside showed that the LA network is providing lower levels of skid resistance compared to the National Highways sub-network, but the results from Norfolk demonstrated a good level of agreement between networks.

6.2.6 Summary

The results of the local authority comparison can be summarised by the following general observations:

- The NH network provides a higher overall level of condition (in terms of smoothness, texture and skid resistance, and lower levels of rutting) than the majority of LAs.
- The above statement is also true for the TS and WG networks, with the exception of rutting, where these networks performed similarly to the LAs.
- It is currently not possible to draw conclusions on the comparison of the cracking distributions due to the differences in survey methods that are used to measure cracking.

7 Discussion and recommendations

This section presents a discussion of the results and provides recommendations for future work. Note that, whilst the above results sections have focussed on the data only, in this section, the Authors' understanding of the measurements and their context within pavement engineering has been used to add context to the results of the statistical analysis, and to derive recommendations for the focus future work.

7.1 The condition parameters

7.1.1 Ride quality (enhanced Longitudinal Profile Variance (eLPV) and International Roughness Index (IRI)

For ride quality, measured as 3m and 10m eLPV, there were no substantial differences observed between the UK national networks. When compared with the LA road networks, the NH network appears to provide better ride quality (i.e. lower levels of eLPV).

However, when the ride quality was expressed as IRI, which enables comparison with the RWS network, it could be seen that the RWS network provides higher levels of ride quality than the UK networks. This observation persisted for all road classes.

When comparing the condition of the national networks with their in-service requirements it was observed that both the RWS and the UK networks exceed their requirements. RWS have adopted stricter in-service requirements (4 mm/m) than those in place in the UK (~7.5 mm/m). We might expect the different requirements to explain the differences between the networks, as they could be representative of the levels of ride quality to which the networks are managed. However, they do not *fully* explain the differences, because the level to which the UK networks are exceeding their in-service requirements is different to the level to which the RWS network is exceeding its requirements. It is hypothesised that, given that the UK networks are already markedly exceeding their requirements, there would be a limited necessity under current maintenance practice to further improve ride quality - i.e, from a UK requirements perspective, the networks are performing well in terms of ride quality.

The deeper dive into ride quality included an assessment of material type. It should be noted that, due to a fundamental difference in the materials used on the UK and RWS networks, the material type comparison was not able to include the substantial proportion (~90%) of the RWS network. The RWS network is predominantly surfaced with porous asphalt which is not typically used in the UK (primarily thin surface course [TSCS] and hot rolled asphalt [HRA]). This presents a challenge to the material type assessment. It does not enable differences in network wide condition that might be related to differences in the properties of porous asphalt materials to be fully understood. This could include differences in maintenance approaches that are specific to porous asphalts (e.g., it may be necessary to carry out more frequent renewals on porous asphalt because to their general propensity for ravelling). Nevertheless, there are portions of the RWS network (totalling ~665 km) that use comparable materials to those used in the UK, which can be used to investigate the influence of material type to some degree.

For ride quality, material type did not provide a strong explanation for the differences between the RWS and UK networks. Ride quality on sections of the RWS network paved with porous asphalt was not found to be substantially different from sections paved with the same types of materials as those used in the UK. . Therefore, the benchmarking does not provide evidence that the use of porous asphalts leads to better levels of ride quality than other materials (an indication supported by the deeper dive plots). There may be further variables influencing the differences in ride quality between the networks, including:

- A stricter implementation of the in-service requirements than comparator networks (see following section).
- Differences in maintenance regimes between the UK and RWS networks (see below).
- The pavement construction. For example, asphalt surface materials laid on a concrete base may provide different levels of ride quality than asphalt surface materials laid on an asphalt base.

The RWS network appears to provide smoother ride quality notwithstanding the amount of traffic using the network over time (‘total trafficking’). It was found that differences in the separation of the UK and RWS networks were broadly similar for all levels of trafficking.

The analysis of material ages showed that the average age of road surfaces on the RWS network are lower than on the National Highways network. This could suggest that maintenance practice on the RWS network has resulted in treatments being carried out at more frequent intervals, resulting in better ride quality. However, further work would be required to determine whether the more youthful age profile in the RWS network (and hence perhaps the better ride quality) is a result of the application of more demanding in service requirements leading to more maintenance, or is because the material types used have led to a need for more frequent maintenance to be undertaken.

7.1.2 Rutting

Substantial differences in rutting were observed between the RWS/NH and WG/TS networks, and the NH network provided lower rutting values than comparable local authorities. As for ride quality, all the networks are exceeding their in-service requirements for a large proportion of their network lengths, with both the NH and RWS networks exceeding their requirements by a substantial margin. The assessment of the in-service requirements did not fully explain the differences observed between the networks. This is for similar reasons to those observed for ride quality, namely that the networks are exceeding their requirements by a greater margin than the differences between the average network values. Because the networks are markedly exceeding their in-service requirements it can be inferred that rutting would not be considered a prominent problem by the operators of these networks.

The deeper dive into age, material type, and total trafficking provided a partial explanation for the differences between the networks, as differences in condition were less pronounced for road surfaces of comparable age, material type, and total trafficking. The results of the deeper dive also suggested an interdependency between material type and age which could be investigated as part of future work.

The assessment of rutting by carriageway type went some way to reducing the differences observed in the network level assessments. This is particularly evident for motorways and dual carriageways, which demonstrated the largest amount of agreement between sub-networks.

An assessment of carriageway type could therefore offer insight as part of future work. This assessment could be combined with an assessment of trafficking. It is hypothesised that single carriageway roads on the NH networks would mainly comprise 'major' roads with relatively large amounts of trafficking, whereas single carriageways on the WG and TS could comprise more rural roads carrying lower volumes of traffic.

7.1.3 Skid resistance

The national benchmarking results showed similar average skid resistance between the NH and TS networks, but a large difference between the NH/TS (lower skid resistance) and WG/RWS networks (higher skid resistance). Overall, the NH network provided the lowest skid resistance values of all networks. The NH network provided higher skid resistance values than the Humberside local authority network, but had skid resistance values largely comparable to the Norfolk local authority network.

After the in-service requirements were taken into account (i.e. by plotting the distribution of differences from in-service requirement), a better agreement between the performances of the networks was observed. That is to say that the distributions of difference values[11] overlapped to a greater degree than the skid resistance values alone.

Skid resistance is the only parameter for which the consideration of in-service requirements brought the condition of the networks into alignment. This is likely to be a combination of the relatively similar thresholds for skid resistance adopted in the UK, combined with the way in which skid resistance is managed. These observations suggest that:

1. The skid resistance of the national networks is managed in a more direct way to some of the other parameters.
2. The difference in the UK networks is largely driven by differences in road site categories (roundabouts, approaches to junctions etc…) prevailing on each of the networks. In other words, it could be the case that the NH and TS networks have a greater amount of low risk roads (requiring lower skid resistance) than the WG network.

The first of the points above is supported by UK skid resistance policy. Skid resistance is considered a safety related parameter. A formal process is applied in which locations experiencing sustained reductions in skid resistance are subject to investigation to identify whether remedial action is required. In contrast, the other condition parameters are considered to relate to the functional or structural condition of the pavement. In other words, these other parameters are managed in a holistic way whereas skid resistance is managed in a more direct way. For the National Highways network, decisions on maintenance requirements are made in the light of the overall condition which takes into account a range of different condition elements parameters as part of the wider asset management process.

[11] The difference between the measured skid resistance and in-service requirements.

Therefore, it may be beneficial to develop a better understanding of the ways in which the in-service requirements of all road condition parameters are managed on each of the networks, to help understand the causal link between in-service requirements and network condition.

In addition to the discussion presented above it should be noted that, even after adjusting for in-service requirement, the RWS network provides the greatest skid resistance values of all of the networks. In this case it is unlikely that better skid resistance in the Netherlands is related to the makeup of the road network in terms of site category, as RWS employ very different skid resistance standards to the UK networks. To further understand the skid resistance behaviour of the RWS network, three observations can be made:

1. The in-service requirements for porous materials are lower than those for more dense materials such as those predominantly used in the UK.
2. The average skid resistance of *porous asphalt materials* is approximately 0.54 pSC, and
3. The average skid resistance of TSCSs and other more dense asphalt materials is approximately 0.48 pSC.

These observations suggest that, despite having a lower in-service requirement, the porous asphalt materials used on the RWS network provide a higher overall level of skid resistance.

7.1.4 Cracking

For cracking the benchmarking exercise was limited to comparing the UK networks, as the data for the RWS was not comparable. In addition, we have noted that known differences between the survey methodologies employed on the NH and other UK networks could lead to higher levels of cracking being reported on the NH network. This was found in the national benchmarking, with the NH network having substantially greater cracking values than observed in the TS and WG networks. This observation was mirrored in the assessment of the LA networks, where the combined results for all LA networks aligned well with the WG and TS networks (all of which characterise cracking using the same methodology). Therefore a more detailed analysis of cracking was not considered appropriate given the risks that comparisons are artificially affected by differences in data collection and analysis methodologies.

7.1.5 Texture depth

The UK networks are provided broadly similar levels of texture depth despite there being some visible differences in the histogram distributions. On the whole, the NH network provided higher texture depth values than comparable local authorities. The RWS network provides slightly lower levels of texture depth than the UK networks. Notably, RWS does not have an in-service requirement for texture depth, whereas the UK networks do. In addition, a high proportion of the lengths of each of the UK networks are exceeding the in-service requirements, to a broadly similar extent.

The overall distributions of texture depth values on the RWS network showed bi-modality (the distributions of values had two peaks). For motorways the lower of the two peaks (at approximately 0.5 mm) was very small but on single carriageway roads this peak was larger.

Interestingly, bi-modality was also observed in the Norfolk, Shropshire, and Suffolk sub-networks of the NH network.

The deeper dive provided evidence to show that material type influences texture depth. For example, substantial differences in texture were observed on the RWS network between dense and porous asphalt materials. It may therefore be the case that the context within which the materials have been used, rather than the attributes of the materials themselves may be influencing the differences observed in the networks. Understanding this would require a further investigation into the parameters (e.g. spatially), and establishing a better understanding of the differences in maintenance practice.

7.2 Recommendations

7.2.1 Understanding differences in network condition

The outcomes of this work suggest that consideration of individual additional explanatory variables (e.g. age, total trafficking, or material type) does not fully explain the differences in network condition observed in the national benchmarking. For example, additional explanatory variables such as age and material type only partly explained the differences in network condition for skid resistance, but not to a degree where it could be confidently stated that either of these parameters were the sole explanator of differences between the networks. The deeper dive also suggested that further insight might be obtained by analysing these variables in combination, rather than in isolation (e.g. by material type *and* material age). For example, the assessment of rutting suggested that some of the variability in network condition could be explained by material age, and partly explained by material type.

These observations demonstrate that the contribution of different factors is complex, and hence there may be a need for more complexity in the analysis to achieve more explanatory power. This was outside the scope of the current study, but it is suggested that such an assessment could be carried out in three ways:

- Extending the deeper dive by testing additional explanatory variables in combination with each other. For example, material type could be further split by age, trafficking rate, or operational environment.
- Further explanatory variables could be collected to provide deeper insight. For example, the NH database holds information relating to road construction (material type and layer thickness) - variables that could influence parameters such as ride quality and rutting. Explanatory variables could also be sought relating to material properties such as aggregate size, polished stone value, or bitumen type (for asphalt surfaces).
- Parameter data could be collected using tools allowing for a like for like comparison of road condition. For example, cracking and fretting on the TS, WG, and RWS networks could be characterised using a single survey method, allowing for a like for like comparison with the NH network, to overcome the difficulties that were encountered when making comparisons in this work.

7.2.2 Maintenance Strategy and the application of in-service requirements

The in-service requirements appear to provide some insight into the reasons for the similarities and differences between networks. Further insight could be gained through an investigation of these requirements, and how they are linked to asset management strategies and policies within the wider context of the management of the networks.

For example, it is the Authors' understanding that one of RWS' key aims is to provide a network that minimises the acoustic exposure of residents close to the network. This contributes to the preference for the use of porous asphalt in the Netherlands. Research (Sanders, Morosiuk, & Peeling, 2014) and (Sanders, 2017) has demonstrated that texture depth on porous materials does not fully characterise their ability to remove water from the pavement surface (which is a primary function of texture depth). Therefore, it is appropriate that RWS do not include texture depth as part of their suite of in-service requirements, but instead focus on fretting, which is a key indicator of the condition of these surfaces. In this example, there is a chain of influence between the aims of the NRA, material specification, the in-service requirement for texture and fretting, and their application. Such aims and strategies will influence all parameters, and further insight could help understand the differences seen in this work. This further work could include:

- Achieving a better understanding of the methodologies through which the in-service requirements are applied. This could include literature and organisational review to better understand the organisational oversight and reporting, management structure, sub-contracting procedures, and funding streams etc; interviewing, surveying, or conducting workshops with stakeholders to understand the policies, strategies, and funding arrangements that drive condition management.
- Carrying out assessment of case studies from real sites. These sites could be assessed through the policies of each NRA, and the maintenance decisions compared so that the 'on-the-ground' effects of each policy could be understood. For each case study site, hypothetical maintenance regimes would be designed based on the asset management strategies and in-service requirements of each of the comparator road authorities. This approach could be used as a basis for comparing the relative cost of the maintenance approaches and modelling the 'on the ground' impact on pavement condition.

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Appendices

Appendix A Data gathering

A.1 Road condition data

A.1.1 National Highways (NH) (English Strategic Road Network)

National Highways provided access and consent to interrogate their pavement management system, Highways Agency Pavement Management System (HAPMS), which contains condition data. Data were extracted using the “SCRIM – CSC Analysis (v.4)” query and the “TRACS – Latest LW Avg YYYYMMDD” data query.

100m reporting lengths are applied to report condition on the NH network . Therefore the queries were used to provide data over 100m reporting lengths. This approach (100m lengths) was extended to the other networks for consistency in the benchmarking. Skid resistance data were available for lane 1, approximately 14,000 km. TRACS data were available for lanes 1, 2 and 3, excluding roundabouts; approximately 34,000 lane km.

A.1.1.1 Skid resistance data (CSC Analysis v.4)

This query reported skid data referenced to section and chainage over 100m lengths. Location referencing and survey information was output as detailed in the following tables. The parameter data highlighted in green are those that were used for the national benchmarking. Note that, although the reporting interval was nominally 100m, the query reports data over shorter lengths where there is a change in site category and/or IL[12] within the 100m length, or where the end of a network section does not fall at a multiple of 100m. For example, for a section length of 220m with a site category/IL change at 40m the following records would be returned from the query 0-40, 40-100, 100-200, 200-220.

[12] Site categories and ILs are defined in NH document CS228 and relate to categories of road type (motorway, approach to junction, etc…) and the threshold skid resistance at those locations.

Table A-1 National Highways skid resistance location referencing data

Heading	Comment
survey_start_date	Date of the survey
Road_number	Name of road the data corresponds to e.g. A1
section_label	Name of section the data corresponds to e.g. 0200A1/102
operational_area_name	Name of National Highways Area that the data corresponds to
xsp_code	Reference to the lane, CL1 is lane 1 in the defined section direction. CR1 is used for single carriageway lengths and corresponds to lane 1 in the opposite direction.
start_chainage	Chainage of start of reporting length
end_chainage	Chainage of end of reporting length

Table A-2 National Highways skid resistance survey data

Data	Heading	Comment
Seasonal correction factor applied	Lecf	Local Equilibrium Correction Factor (LECF) will not be used as the correction is applied in the reporting of the seasonally corrected skid data (correction has been applied)
Seasonally corrected skid data	corrected_scrim_coefficient	Good quality, this is the core parameter for assessment.
Site category	site_definition_code	Supporting information, will be used to investigate differences for subsets of networks
IL	investigatory_level_code	Supporting information
Skid Difference (CSC – IL)	scrim_difference	Good quality

A.1.1.2 TRACS – Latest LW Avg YYYYMMDD

This query reported data referenced to section and chainage over 100m lengths. Sections with a length that was not a multiple of 100m had sub-sections reported at the section end, referred to as “stubs”. The same location referencing information was present in the output for this data as for the “SCRIM – CSC Analysis (v.4)” output. The parameter data contained in the output is given in Table A-3- the items highlighted in green used for the national benchmarking.

Table A-3 National highways TRACS data

Data	Heading	Comment
Left Rut	left_rut	Good quality
Right Rut	right_rut	
Maximum Rut	maximum_rut	
Maximum Rut Category	maximum_rut_category	Indicator – not used
Texture (SMTD)	Texture	Good quality
Left 3m eLPV	left_lpv_3m	Good quality
Right 3m eLPV	right_lpv_3m	
Maximum 3m eLPV	maximum_lpv_3m	
Maximjum LPV 3m Category	maximum_lpv_3m_category	Indicator – not used
Left LPV 10m	left_lpv_10m	Good quality
Right LPV 10m	right_lpv_10m	
Maximum LPV 10m	maximum_lpv_10m	
Maximum LPV 10m Category	maximum_lpv_10m_category	Indicator – not used
Left LPV 30m	left_lpv_30m	Not used - not reported by other Authorities
Right LPV 30m	right_lpv_30m	
Maximum LPV 30m	maximum_lpv_30m	
Maximum LPV 30m Category	maximum_lpv_30m_category	Indicator – not used
Bump	Bump	Not used - not reported by other Authorities
Noise	noise_db	
Lane Fretting	lane_fretting	Fretting and cracking data are known to have lower levels of repeatability. Although network level comparisons can be undertaken, care should be taken with smaller datasets.
Lane Cracking	lane_cracking	
Left Wtrk Cracking	left_wtrk_cracking	Not used - not reported by other Authorities
Right Wtrk Cracking	right_wtrk_cracking	
Maximum Wtrk Cracking	maximum_wtrk_cracking	
Left retroreflectivity	nearside_retroreflectivity	Not used - not reported by other Authorities
Right retroreflectivity	offside_retroreflectivity	

A.1.2 Transport Scotland (TS) (trunk roads in Scotland)

The condition data for Transport Scotland is contained in a pavement management system managed by a third party consultant. The full dataset was provided which comprised three files, the content of each is discussed below.

A.1.2.1 TRL_TS_Scanner_ALL.csv

This file contained data in 10m spacing and included 702,761 records representing approximately 7,027 lane km. These data were aggregated to 100m lengths. Location referencing and parameter information are summarised in the following tables.

Table A-4 Transport Scotland location referencing data

Heading	Comment
SECTION_UID	Integer representing the section to link to other datasets in the database
CROSS_SECTIONAL_POSITION	Reference to the lane in the section, CL1 is lane 1 in the main direction of the section. CR1 is used for single carriageway lengths and corresponds to lane 1 in the opposite direction.
START_METRES	Chainage of start of reporting length
END_METRES	Chainge of end of reporting length
SURVEY_DATE	Date of the survey
GPS_EASTING	OSGR easting and northing of report length (note not specified which part of the length this corresponds to)
GPS_NORTHING	

Table A-5 Transport Scotland SCANNER data

Data	Heading	Comment
3m LPV Left wheel track	LPV_03_LWT	Superseded by eLPV, will not be used
10m LPV Left wheel track	LPV_10_LWT	
30m LPV Left wheel track	LPV_30_LWT	
3m eLPV Left wheel track	eLPV_03_LWT	Good quality
10m eLPV Left wheel track	eLPV_10_LWT	
3m eLPV right wheel track	eLPV_03_RWT	
10m eLPV right wheel track	eLPV_10_RWT	
Rut in left wheel track	LWT_RUT	Good quality.
Rut in right wheel track	RWT_RUT	
SMTD in left wheel track	LWT_TEX_SMTD	Good quality
SMTD in middle of lane	MID_TEX_SMTD	
SMTD in right wheel track	RWT_TEX_SMTD	
Area of Cracking	AREA_OF_CRACKING	Lower quality, cracking data are known to have lower levels of repeatability. Comparisons on network level can be undertaken, however care should be taken for smaller datasets.

A.1.2.2 TRL_TS_SCRIM_SUMMARY_ALL.csv

This file contained data in variable spacing and included 78,905 records. The reporting interval is governed in part by the extent and type of the site category and IL assigned. The interval is 100m unless there is a change in the site category and/or IL, in which case the 100m length is split between the categories. For example if there is a site category/IL change at 40m then the following records would be seen 0-40, 40-100, 100-200 etc. (similar to the way National Highways data are reported). The same location referencing information as above was provided in this file. The parameter data contained in the file is given in Table A-6.

Table A-6 Transport Scotland skid resistance data

Data	Heading	Comment
Seasonally corrected skid measurement	MSSC	Good quality
Investigatory Level (IL)	SCRIM_INVESTIGATORY_LEVEL	Supporting information
MSSC – IL	SCRIM_DIFFERENCE	Good quality
Site Category	SCRIM_SITE_CATEGORY_NAME	Supporting information, will be used to investigate differences for subsets of networks

A.1.3 *Welsh Government (WG) (trunk roads in Wales)*

Welsh Government condition data are managed by the same third party consultant as the Transport Scotland data. A full dataset was provided which comprised of three files, identical in format and content to those relating to the Transport Scotland network, the coverage of each file for the dataset is summarised below.

A.1.3.1 *TRL_WG_Scanner_ALL.csv*

This file contained data in 10m spacing and included 335,199 records representing approximately 3,351 lane km.

A.1.3.2 *TRL_WG_SCRIM_RAW_ALL.csv*

This file contained data in 10m spacing and included 336,803 records representing approximately 3,368 lane km.

A.1.3.3 *TRL_WG_SCRIM_SUMMARY_ALL.csv*

This file contained data in variable spacing and included 41,167 records.

A.1.4 *Rijkswaterstaat (RWS) (trunk roads in the Netherlands)*

A network wide dataset was provided by Rijkswaterstaat for the Netherlands trunk road network. This was provided in an Excel workbook, at 100m spacing, and included 69,098 rows. The RWS network is split in to discrete 100m sections *without the inclusion of stubs*. Location referencing information and parameter information in the file is detailed in the following tables.

Table A-7 Rijkswaterstaat location referencing data

Heading	Comment
Weg	Integer denoting road
baan	Direction
Strook	Lane number.
Van	Chainage of start of reporting length
Tot	Chainge of end of reporting length
gpsvanx	Longitude and Latitude at start of length
gpsvany	
gpstotx	Longitude and Latitude at end of length
gpstoty	
Meetdatum	Survey date for survey providing details on texture, fretting, cracking, ride quality and rut depth.
Meetdatum_SWF	Survey date for survey providing skid resistance data.

Table A-8 Rijkswaterstaat condition data

Data	Heading	Comment
Expected year for maintenance due to fretting	interventiejaarrafeling	Lower quality, fretting data are known to have lower levels of repeatability. Comparisons on network level can be undertaken, however care should be taken for smaller datasets. Also this has been converted into an expected date for treatment rather than the measurement.
Expected year for maintenance due to cracking	interventiejaarkrk	Lower quality, cracking data are known to have lower levels of repeatability. Comparisons on network level can be undertaken, however care should be taken for smaller datasets. Also this has been converted into an expected date for treatment rather than the measurement.
MPD in right wheel track	MPD_RS	Good quality
Skid resistance survey speed	Meetsnelheid_SWF	Supporting information for conversion of skid resistance to UK scale.
Skid measurement	Meetwaarde_SWF	Skid measurement uncorrected for speed or seasonal variation - will be converted for use.
Investigatory level for skid measurement	norm_SWF	Set by survey speed and surfacing type (porous or non-porous). – will not be used.
Roughness	IRI	Good quality
Rut in left wheel track	RSD_LS	Good quality
Rut in right wheel track	RSD_RS	

A.1.5 English Local Authorities (LAs) (English non-trunk roads)

England has 333 individual Local Authorities (LAs) responsible for the management of local road networks. 85 LA areas geographically include a portion of National Highways' road network. Benchmarking the national network against this number of local networks was outside the scope of this study. To obtain a representative sample of local networks for the benchmarking process a subset of local authorities was therefore selected to represent local road networks having a range of condition - relatively high, moderate, and low values of the SCANNER RCI, for principal networks over 100km in length, but also geographically distributed over the country. These were; Cumbria, Humberside, Kent, Norfolk, North Yorkshire, Shropshire, Somerset, Suffolk, and Surrey.

As TRL holds a national database of SCANNER data for its role as auditors of SCANNER, permission to use the SCANNER data held by TRL for these networks was sought from the individual LAs. Skid resistance data for these networks were not available from TRLs database and hence was sought from the LAs directly. Skid resistance data were provided for Norfolk and a sub-set of the Humberside network.

A.2 Additional explanatory variables

For this work, additional explanatory variables are defined as information not relating to pavement condition, that may be used to gain possible insight into the results of the national benchmarking, for example the age of the road.

A.2.1 National Highways

The HAPMS database provides a range of additional explanatory variables that can be obtained via specific queries, and the WEBTRIS database also provided trafficking information, as detailed below.

A.2.1.1 Section Data inc. HA Admin Data

This query provided a single row of data for each section and includes “section_label” which was used to match up the data to the condition data. This data query provided the additional information listed in Table A-9.

Table A-9 National Highways section data

Data	Heading	Comment
Road class	Road_class_name	Identifies if the road is A, M or A(M)
Section type	Section_function_name	Main Carriageway, slip road, roundabout or Ox Bow Lay-by
Single or dual carriageway (code)	Single_or_dual_code	Short code to identify if section is a single carriageway or dual carriageway
Single or dual carriageway (name)	Single_or_dual_name	Name denoting if section is a single carriageway or dual carriageway
Urban or Rural	Environment_name	Denotes if the section is an urban or rural section.
Local Authority	Local_authority_name	Which local authority the section is in the same geographic area of.

A.2.1.2 Construction – All Layers

This query provided a single row of data for each construction layer on the network (for each wheel path and construction length). It included section_label, start_chainage, end_chainage and xsp_code so that construction could be matched to the condition data. Note the xsp_code is split into the left and right wheel path, e.g. CL1L and CL1R is the left and right wheel paths of lane one (in the main direction of the section). The content is summarised in Table A-10.

Table A-10 National Highways construction data

Data	Heading	Comment
Traffic accumulation date (TAD)	Traf_acc_date	The date of the last major structural work on this length. This is used in residual life analyses for deflection measurements. Therefore not used in this work.
Layer	Layer_sequence	Position of the layer in construction for this construction length. 1 coresponds to the bottom layer, and increases towards the surface.
Material name	Material_name	Name of the material in this layer
Date laid	Date_laid	Date that this layer was laid
thickness	thickness	Thickness of the layer

A.2.1.3 Trafficking data

Traffic data were obtained from the WebTRIS database in the form of HGV Average Annual Daily Flow (AADF) for each road section and lane.

A.2.2 Transport Scotland

Additional explanatory variables for the TS network were provided from the same pavement management system as the condition data. Therefore it was possible to obtain these data for all lengths for which the condition parameter data was available. It comprised of two files. The content of each file are discussed below

A.2.2.1 TRL_TS_CONSTRUCTION.csv

The data in this file had variable spacing as each row corresponds to a construction length. It contained location referencing details to match up to the condition data. This location referencing data are:

- SECTION_UID
- CROSS_SECTIONAL_POSITION
- START_METRES
- END_METRES

This dataset provided the additional information listed in Table A-11.

Table A-11 Transport Scotland construction data

Data	Heading	Comment
Traffic accumulation date (TAD)	MAJOR_STRENGTHENING_DATE	The date of the last major structural work on this length. This is used in residual life analyses for deflection measurements. Therefore not used in this work.
Polished stone value	PSV	The PSV used in the surfacing
Date laid	SURFACE_DATE	Date of the surfacing
Surface Type name	SURFACE_TYPE_NAME	Surfacing type
Surface source	SURFACE_SOURCE_NAME	Quarry for the material
Surface specification	SURFACE_SPECIFICATION_NAME	Additional details on the surfacing not used in this work.
ESBM	ESBM	Equivalent sound bituminous material (used in Deflection residual life calculations)
Aggregate Abrasion Value	AAV	A property of road stone relating to its abrasion resistance.
BITUMINOUS thickness	TOTAL_BITUMINOUS	Thickness of bituminous in construction layers
CEMENT thickness	TOTAL_CEMENT	Thickness of Cement in construction layers
GRANULAR thickness	TOTAL_GRANULAR	Thickness of Granular construction in construction layers

A.2.2.2 TRL_TS_TRAFFIC.csv

The data in this file is provided by section and contains SECTION_UID and CROSS_SECTIONAL_POSITION to match up to the condition data. This dataset provided the additional information shown in Table A-12.

Table A-12 Transport Scotland trafficking data

Data	Heading	Comment
Date	COUNT_DATE	Date on which the traffic count was made
COMMERCIAL AADF	TOTAL_COMMERCIAL_AADF	Average Annual Daily Flow for commercial vehicles
AADF	TOTAL_AADF	Average Annual Daily Flow for all traffic

A.2.3 Welsh Government

Additional explanatory variables for the WG network was obtained in the same approach and format as for the TS network.

A.2.4 Rijkswaterstaat (RWS)

Additional explanatory variables for the RWS network was supplied in the same data table as the condition data, and is summarised in Table A-13. The coverage of additional explanatory variables in the final dataset was the same as for the parameter/condition data.

Table A-13 Rijkswaterstaat additional explanatory variables

Heading	Comment
A/N	Road type, A=Motorway, N=National Highway (equivalent to A-road in UK)
type	Carriageway type, tweebaans=dual carriageway, enkelbaans=2way verbindingsweg= slip road
aantalStrokenBaan	Number of permanent lanes (i.e. not hard shoulder)
deklaagsoort	Surface layer, see lookup tables in spreadsheet for the different types.
aanlegdatumdeklaag	Surfacing date
L2	Traffic for medium trucks (AAD)
L3	Traffic for heavy trucks (AAD)

A.2.5 UK Local authorities

Additional explanatory variables for the UK LAs were not collected as they were not required for the analysis.

A.3 Data aggregation for national benchmarking

As noted above the benchmarking used 100m length aggregation, to match the standard 100m reporting interval used by National Highways. Data for the RWS network and corrected skid resistance data for the TS and WG networks were provided as 100m lengths. Data from the WG and TS networks (excluding corrected skid resistance data) were provided over 10m lengths but 100m averages were calculated for this data to ensure a like for like comparison between the datasets.

However, for either of the above (supplied as 100m or aggregated up from 10m), ends of sections that did not form complete 100m lengths were referred to "*stubs*". In addition, the skid resistance data for the UK authorities included splits in the lengths due to changes in site category and/or IL. For example, if there is a site category/IL change at 40m then the following records would be seen 0-40, 40-100, 100-200 etc. Such lengths were referred to as "*IL Stubs*".

Table A-14 Example of the separation of sub-sections into IL stubs

Chainage (m)	IL Category	Notes
0	Category α	The first 100m sub-section contains two IL categories; α and β. Two stubs will therefore be returned relating to each IL category.
10		
20		
30		
40	Category β	
50		
60		
70		
80		
90		
100	Category γ	The second 100m sub-section contains one IL category; γ. No stubs will therefore be returned.
110		
120		
130		
140		
150		
160		
170		
180		
190		

A.4 Combining the condition data and additional explanatory variables

To carry out the deeper dive (Section 5) it was necessary to combine the condition data with the additional explanatory variables. An important consideration in combining these datasets was the inclusion of material type data. In a similar way to the creation of stubs resulting from changes in skid resistance IL, additional stubs were created through the inclusion of material type data.

Returning to the example given in Table A-14, let in now be assumed that Material A persists between 0 and 60m, Material B between 60 and 150m, and Material C between 150 and 200m. Based on this example, stubs would be created as presented in Table A-15. Table A-15 demonstrates that the approach has the propensity to result in substantially more stub lengths than when assessing skid resistance alone.

Table A-15 Example of the separation of sub-sections into IL/material type stubs

<table>
<tr><th>Chainage (m)</th><th>IL Category</th><th>Material type</th><th>Notes</th></tr>
<tr><td>0</td><td rowspan="4">Category α</td><td rowspan="6">Material A</td><td rowspan="4">**Stub 1**: IL Category α and Material A</td></tr>
<tr><td>10</td></tr>
<tr><td>20</td></tr>
<tr><td>30</td></tr>
<tr><td>40</td><td rowspan="6">Category β</td><td rowspan="2">**Stub 2**: IL Category β and Material A</td></tr>
<tr><td>50</td></tr>
<tr><td>60</td><td rowspan="9">Material B</td><td rowspan="4">**Stub 3**: IL Category β and Material B</td></tr>
<tr><td>70</td></tr>
<tr><td>80</td></tr>
<tr><td>90</td></tr>
<tr><td>100</td><td rowspan="10">Category γ</td><td rowspan="5">**Stub 4**: IL Category γ and Material B</td></tr>
<tr><td>110</td></tr>
<tr><td>120</td></tr>
<tr><td>130</td></tr>
<tr><td>140</td></tr>
<tr><td>150</td><td rowspan="5">Material C</td><td rowspan="5">**Stub 5**: IL Category γ and Material C</td></tr>
<tr><td>160</td></tr>
<tr><td>170</td></tr>
<tr><td>180</td></tr>
<tr><td>190</td></tr>
</table>

A.5 Data handling tools

The collation and aggregation of data was carried out using SQL server management studio (SQL) and the results of the processing stored as CSV files. A pre-processing exercise (see next section) was carried out using the mathematical manipulation (numpy and pandas), statistical analysis (scipy.stats and statistics), and data visualisation (matplotlib) tools available in Python.

Appendix B Derivation of comparable parameters

B.1 Ride quality (eLPV and IRI)

Ride quality is reported using different measures for the UK and RWS networks (eLPV and IRI respectively). IRI is a single measure of ride quality, whereas eLPV assesses ride quality over different wavelengths (3m, 10m and 30m wavelengths are used by NH).

Because eLPV at 3m and 10m wavelengths was available for all UK networks, a comparison of these networks was carried out using those parameters. A comparison between the UK and RWS networks was carried out by estimating the IRI from the 3m and 10m eLPV measurements using a formula obtained in previous TRL research (TRL CPR 1553, unpublished), Equation 2.

$$IRI \approx Maximum\left(\sqrt{[10 \times (Avg\ 3m\ eLPV)]/3} + \sqrt{Avg\ 10m\ eLPV} - 0.1\,, 0\right)$$

Where:

- Avg 3m eLPV is the average 3m eLPV from both wheelpaths.
- Avg 10m eLPV is the average 10m eLPV from both wheelpaths.
- Maximum (f(x),0) is the positive part of the result of f(x)
- e.g. IF f(x) > 0 THEN IRI = f(x) ELSE IRI = 0.

Equation 2 Estimating IRI from eLPV

B.2 Texture depth (SMTD and MPD)

Texture depth is reported as SMTD (Sensor Measured Texture Depth) for the UK networks and MPD (Mean Profile Depth) or the RWS network. A relationship between SMTD and MTD has been empirically derived in previous (unpublished) TRL research (Equation 3). As the majority of the available texture data was in SMTD, the MPD data from the RWS network was used to estimate SMTD (pSMTD).

$$pSMTD = \frac{MPD}{1.21}$$

Equation 3 Estimating SMTD from MPD

B.3 Skid resistance

UK Road Administrations utilise the sideway-force coefficient routine investigation machine to measure skid resistance, which reports SC. For network assessment the UK administrations apply factors to account for test speed, seasonal, and between year effects, and report the skid resistance as CSC (for the NH network) and MSSC (for the TS and WG networks). For the RWS network, the SeitenKraftMessverfahren (SKM) is used which reports skid resistance as SWF. Although the skid resistance devices used by the UK authorities and RWS are similar, there are some key differences; these are:

- Different test tyres are used resulting in the RWS data being 4-8% higher.
- UK data are corrected to a single speed (50km/h). RWS data are collected at different speeds (40, 60 and 80km/h) and not corrected to a single speed.
- UK data has an adjustment factor applied (known as the "index of SFC"). This is achieved by multiplying the data by 0.78.
- The UK applies seasonal correction, and the NH network applies a between year correction.

Existing relationships for the elements listed above were used to derive an equation for predicting SC based on SWF values (Equation 4), the full process describing its derivation is provided in Appendix C.

$$pSC = \frac{0.78 \cdot SWF(s) \cdot (-0.000152s^2 + 0.00477s + 0.799)}{106}$$

Where:

- SWF(s) is the SideWay force measured at speed s
- s is survey speed in km/h.

Equation 4 Estimation of SC from SWF and survey speed

For the NH network, within-year and between-year seasonal variation are accounted for in the Characteristic Skid Coefficient (CSC). For the RWS data, it is not possible to produce a pCSC value because of the way in which skid resistance surveys are carried out. To assess the effect of seasonal correction on the distribution of skid resistance values at a national level, Figure B-1 presents the distribution of SC and CSC values for a sub-set of the NH network. Figure B-1 shows that there is only small difference between the distributions of SC and CSC values. The difference in distributions is smaller than the uncertainty associated with converting skid measurements made on the RWS network from pSC to pCSC and therefore it was decided that it would be acceptable to compare the RWS pSC directly with CSC.

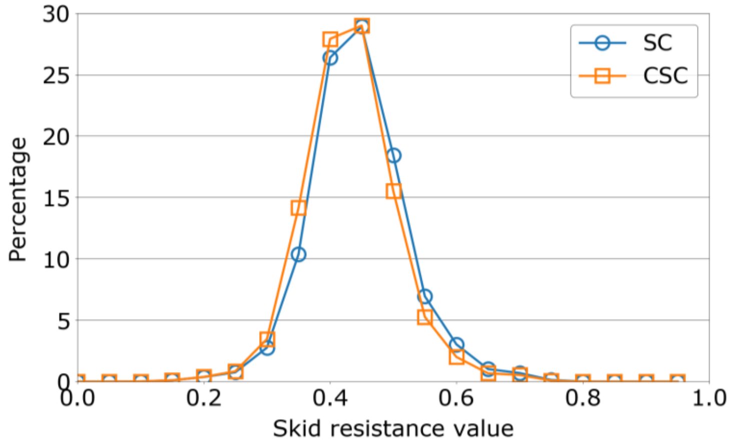


Figure B-1 The distributions of SC and CSC values for a sub-set of the NH network

B.4 Cracking and Fretting

B.4.1 Cracking characterisations using TRACS and SCANNER

On UK national networks cracking data are provided using similar survey methods, but there are substantial differences between the way the data are delivered. The WG and TS categorise cracking using the Surface Condition Assessment for the National Network of Roads (SCANNER) methodology, whereas NH categorise cracking using the Traffic Speed Condition Survey (TRACS). These methodologies use image and laser-based systems to collect raw data (greyscale images and 3D shape), but the set-up of the processes applied to categorise cracking are different.

The standard approach for the reporting of cracking in the SCANNER survey was established in the 2010’s and since then the requirements for cracking have been benchmarked to the performance (and sensitivity to detection of cracking) established at that time. However, whilst earlier generations of TRACS surveys were fundamentally similar to SCANNER, the data assessed in this report was collected by the 4th generation of TRACS. On-going developments in the processing of the TRACS raw data have resulted in a higher level of sensitivity to cracking than established for SCANNER. This is demonstrated in Figure B-2, which presents a histogram of cracking intensities (which are reported as the area of cracking present, as a percentage of the total measured area) reported by TRACS and SCANNER survey devices (in surveys carried out within days of each other) on a test site located on the A329m between Bracknell and Reading. This site is used by TRL in the accreditation tests of the survey devices.

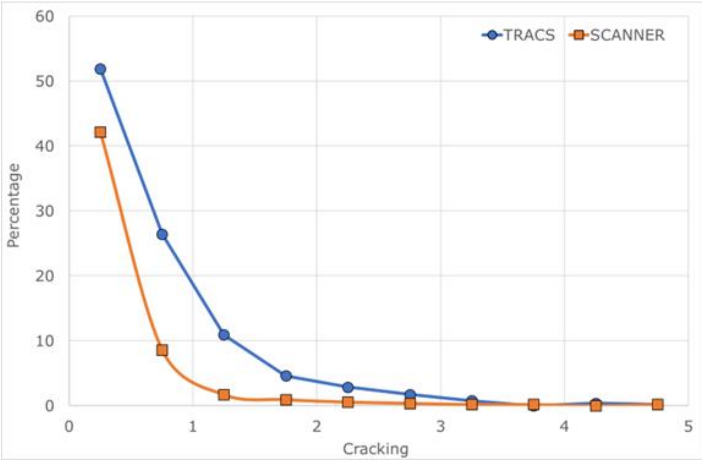


Figure B-2 Comparison of the cracking intensities reported by TRACS and SCANNER on a selected test site

As TRACS reports higher intensities of cracking than SCANNER on the same site, it is expected that this difference could influence comparisons between the network level reporting of cracking on the National Highways and other UK national networks. In addition, the SCANNER survey is deployed on local roads to a similar standard to that deployed by the WG and TS. Therefore, it may be expected that the survey method has a much smaller influence on any comparison between the local authority and the Welsh and Scottish national networks.

B.4.1.1 Cracking and fretting years to maintenance

For the Netherlands it was not possible to obtain a direct measurement of cracking and fretting intensity as these attributes are characterised using a parameter which estimates the amount of time required until maintenance should be carried out; “years to maintenance”. This is not directly comparable to the UK measures of cracking as it requires judgment to be applied to the collected data to convert the measurements into the years to maintenance parameter. It was not possible within the scope of this project to develop a conversion between the UK parameters and years to maintenance. Because of this, it was not possible to make direct comparisons between cracking and fretting parameters between the UK and Netherlands networks, but for completeness, cracking and fretting parameters from the UK networks have been plotted on the same chart as years to maintenance parameters gathered from the RWS network.

Appendix C Derivation of pSC

C.1 Estimating SR (pSR) from SWF

Previous work (Brittain, 2014) empirically derived the following relationship (Equation 5) between measurements made using SKM and sideway-force coefficient routine investigation machine tyres. In the interest of pragmatism, in this work, pSR was calculated using a denominator of **1.06**.

$$\frac{SWF}{1.04} \leq pSR \leq \frac{SWF}{1.08}$$

Equation 5 Predicting SR from SWF

C.2 Estimating SR(50) (pSR(50))

The RWS skid resistance data were speed corrected from pSR using the formula used by the UK NRAs (given in CS228).

$$pSR(50) = pSR(s) \times \frac{-0.0152 \times s^2 + 4.77 \times s + 799}{1000}$$

Where:

- pSR(50) is the estimated skid resistance value normalised to 50 km/h
- pSR is the estimated SR value calculated from Equation 5.
- s is survey speed in km/h.

Equation 6 Estimating SR(50) (pSR(50))

C.3 Estimating SC (pSC)

pSR(50) data were then be converted to pSC using the following formula (given in CS228) (Equation 7).

$$pSC = \left(\frac{pSR(50)}{100}\right) \times 0.78$$

Equation 7 Estimating SC (pSC)

C.4 Deriving a single equation

The equations presented in the previous sections can be combined and simplified into a single equation (Equation 8).

$$pSC = \frac{0.78 \cdot SWF(s) \cdot (-0.000152s^2 + 0.00477s + 0.799)}{106}$$

Where:

- SWF(s) is the SideWay force measured at speed s
- s is survey speed in km/h.

Equation 8 pSC single equation

Appendix D National benchmarking summary dashboards

The results of the national benchmarking are presented in the following sections as a series of dashboards for each condition parameter. The dashboards present:

- For the condition parameters, and the difference between the condition parameters and in service requirements:
    - The distribution of condition values,
    - The distribution of 'difference' values,
    - The results of the Cohen's d-tests,
    - The mean condition value,
    - The 5th percentile of the condition value,
    - The 95th percentile of the condition value.
- For the condition parameters segregated by carriageway type:
    - The distribution of condition values, and
    - The mean condition value.

A full suite of statistics can be found in Appendix E.

As an example, summary statistics for the 3m eLPV distributions have been provided in Table D-1. Here, each column represents the statistics associated with each NRA. The last three rows present the Mean, 5th percentile, and 95th percentile of the distributions. The first four rows present the results of the Cohen's d-test comparing the distributions of each NRA with each other NRA. Cells with 'N/A' indicate that the Cohen's d-test was inappropriate as an NRA would be compared with itself. Cells with 'Not assessed' indicate NRAs that could not be assessed if data for a parameter were not delivered.

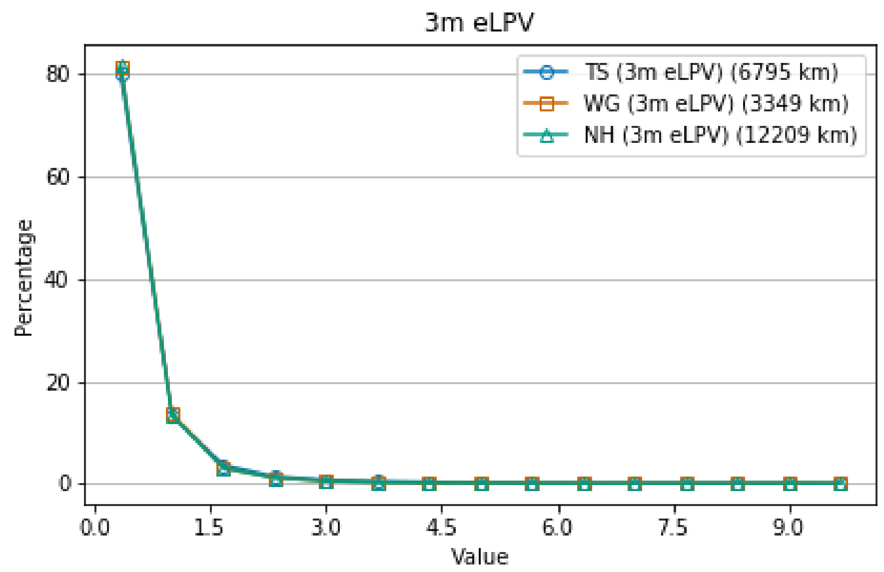
The results of the d-tests have been colour coded as follows; Negligible (Negl.) = Blue, Small = Green, Medium (Med.) = Yellow, Large = Orange.

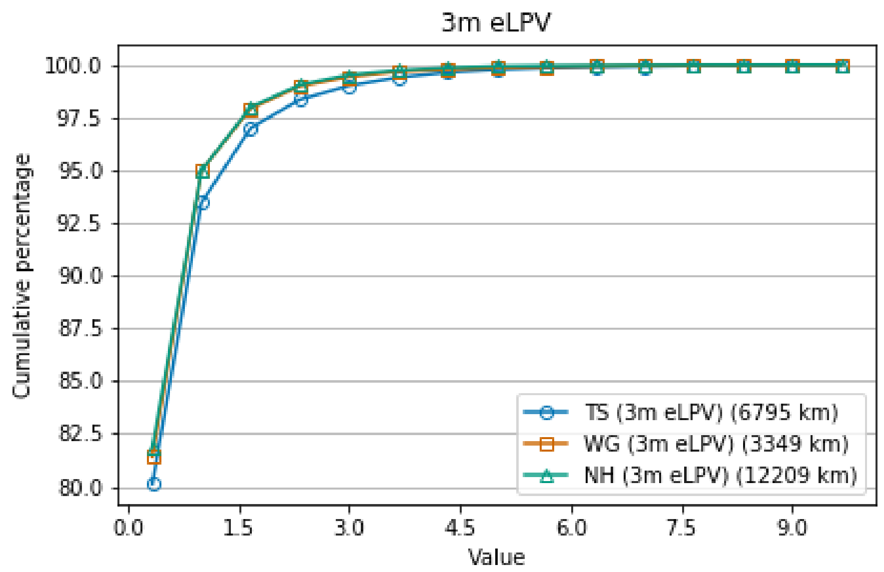
Table D-1 Summary statistics for 3m eLPV distributions

	TS	WG	NH	RWS
TS	N/A	Negl.	Negl.	
WG	Negl.	N/A	Negl.	
NH	Negl.	Negl.	N/A	
RWS	Not assessed			Not assessed
Mean	0.517	0.489	0.459	
5th %tile	0.114	0.117	0.109	
95th %tile	1.687	1.744	1.377	

D.1 3m eLPV

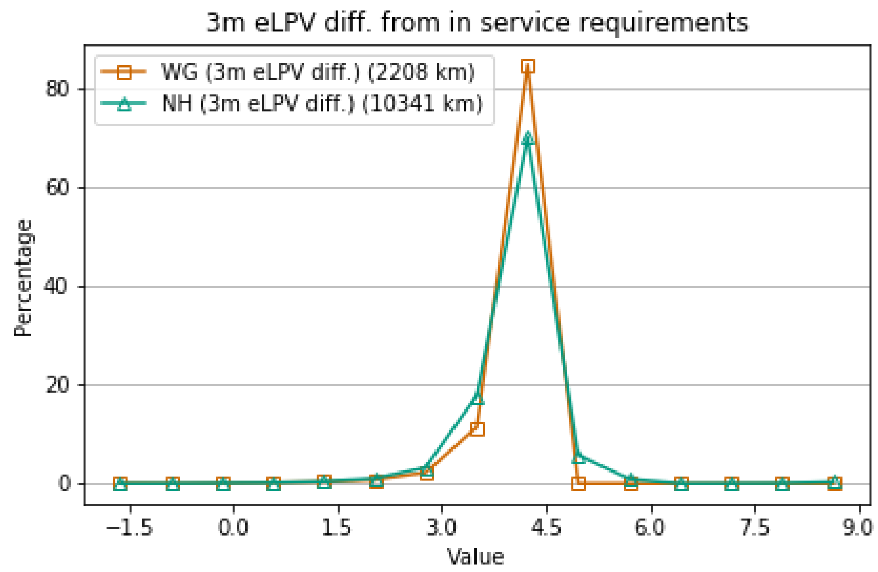
3m eLPV benchmarking

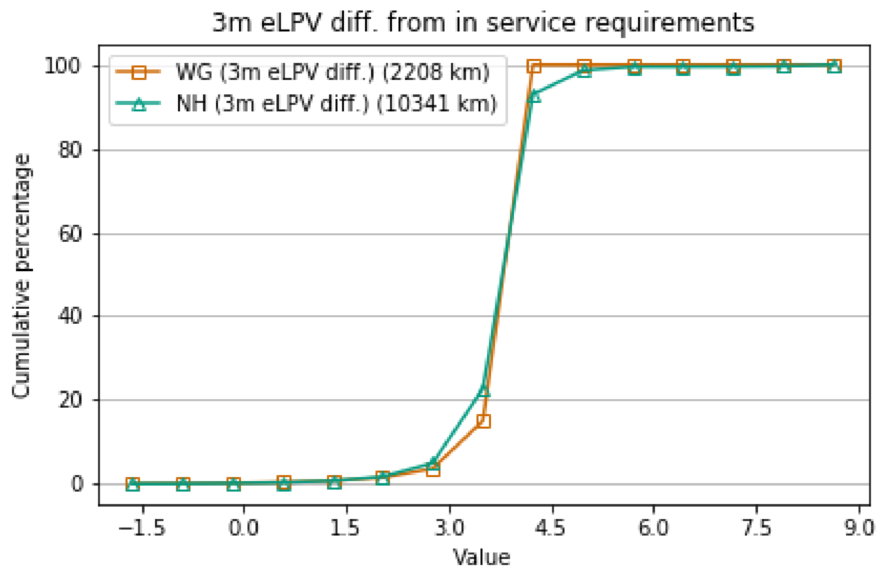




	TS	WG	NH	RWS
TS	N/A	Negl.	Negl.	Not assessed
WG	Negl.	N/A	Negl.	
NH	Negl.	Negl.	N/A	
RWS	Not assessed			
Mean	0.517	0.489	0.459	
5th %tile	0.114	0.117	0.109	
95th %tile	1.687	1.744	1.377	

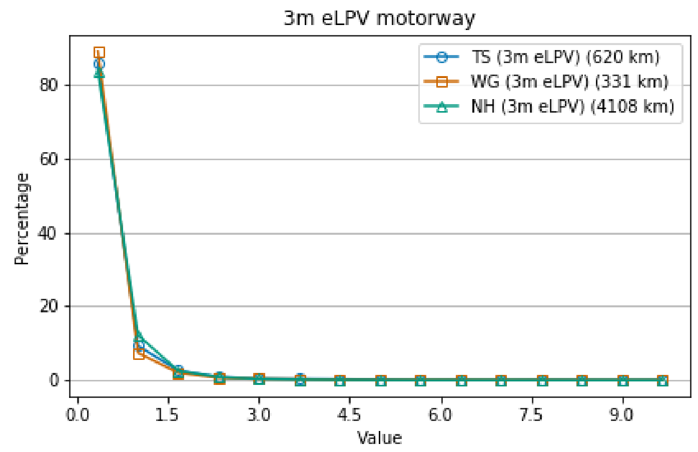
3m eLPV difference from in service requirements

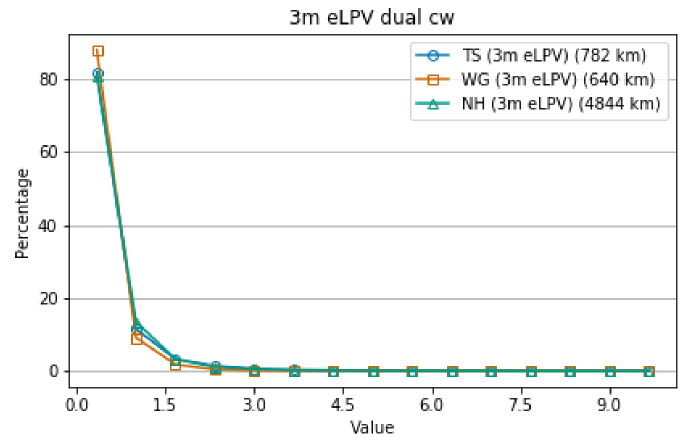


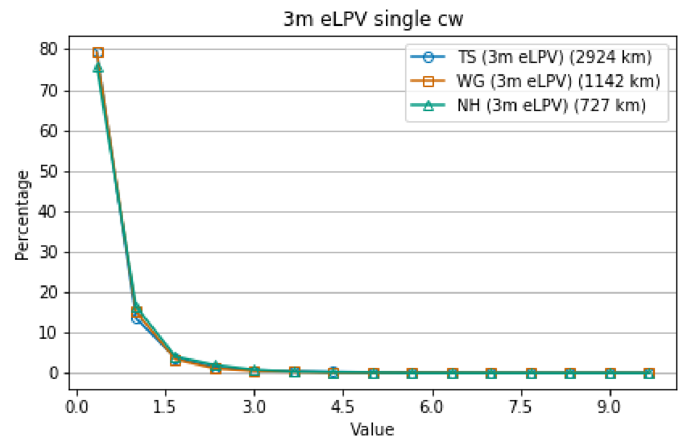


	TS	WG	NH	RWS
TS	Not assessed			
WG	Not assessed	N/A	Negl.	Not assessed
NH		Negl.	N/A	
RWS		Not assessed		
Mean		4.030	4.054	
5th %tile		3.298	3.053	
95th %tile		4.308	5.108	

3m eLPV benchmarking by carriageway type



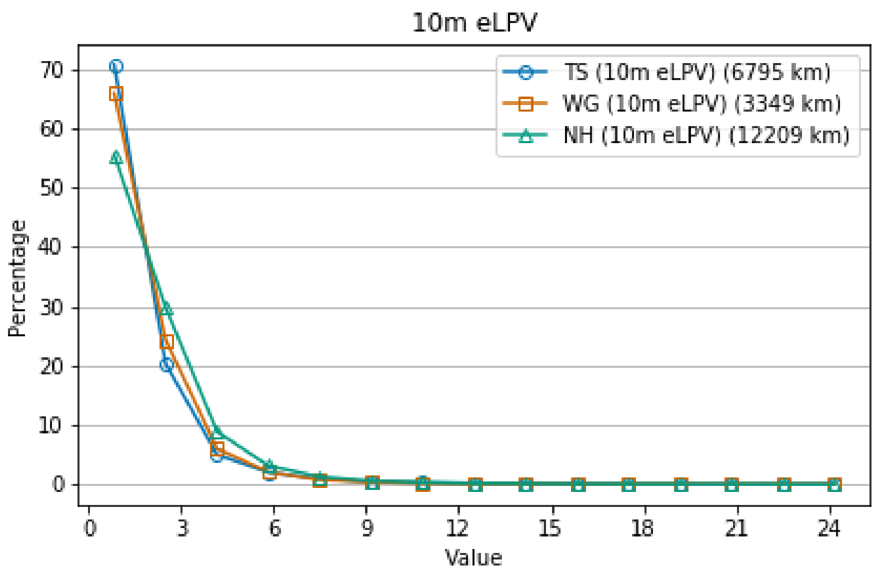


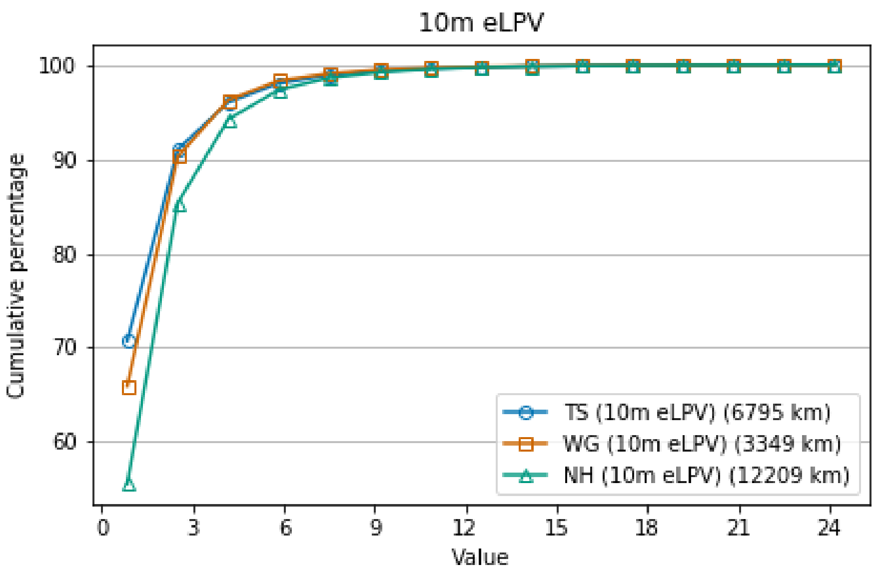


Mean for:	TS	WG	NH	RWS
Motorway	0.445	0.370	0.423	Not assessed
Dual CW	0.501	0.365	0.472	
Single CW	0.539	0.529	0.564	

D.2 10m eLPV

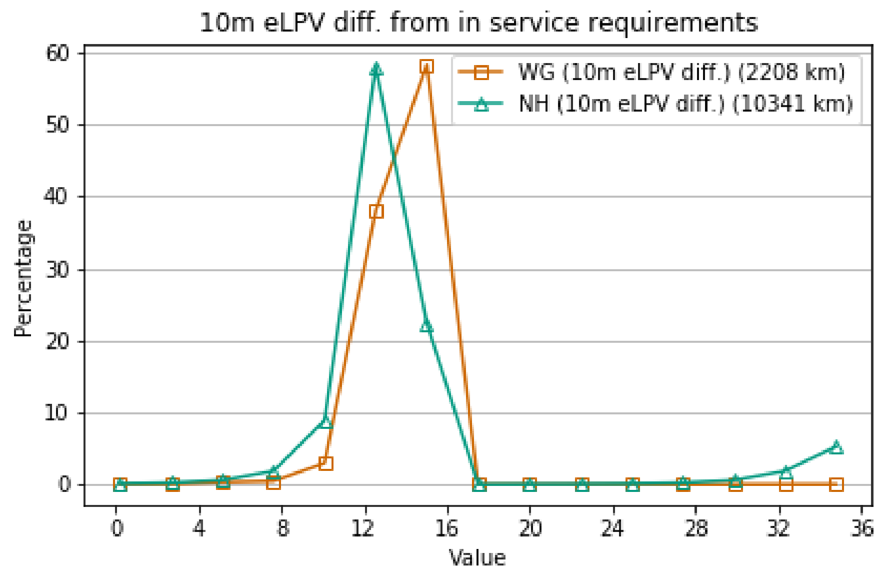
10m eLPV benchmarking

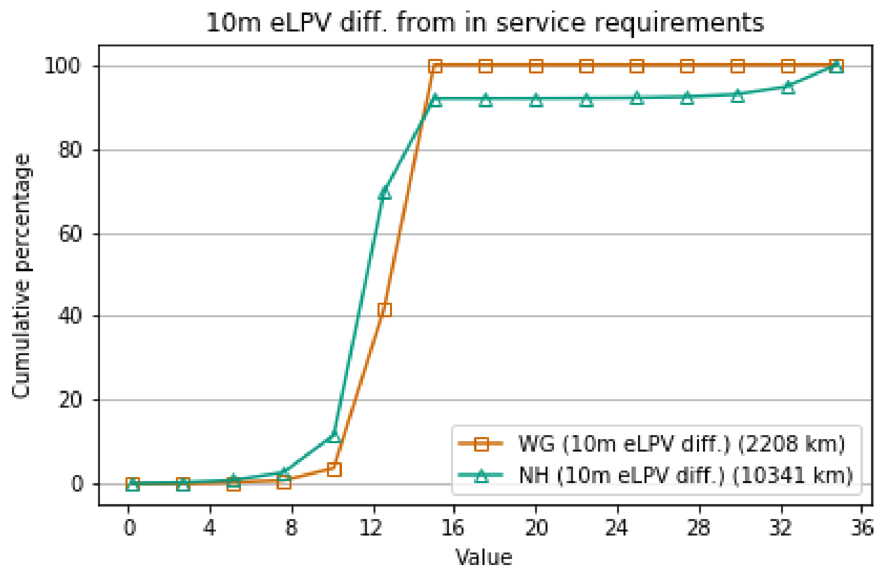




	TS	WG	NH	RWS
TS	N/A	Neg.	Small	Not assessed
WG	Neg.	N/A	Small	
NH	Small	Small	N/A	
RWS	Not assessed			
Mean	1.601	1.699	2.026	
5th %tile	0.366	0.410	0.464	
95th %tile	5.169	5.369	5.753	

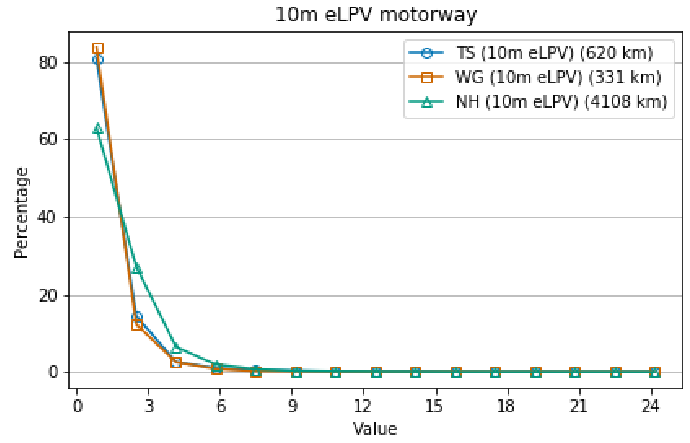
10m eLPV difference from in service requirements

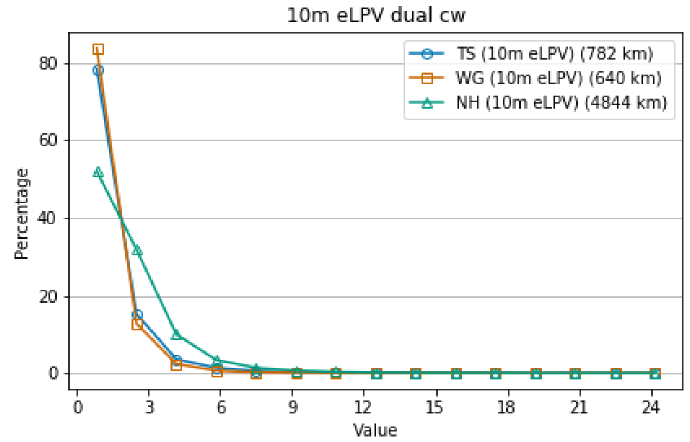


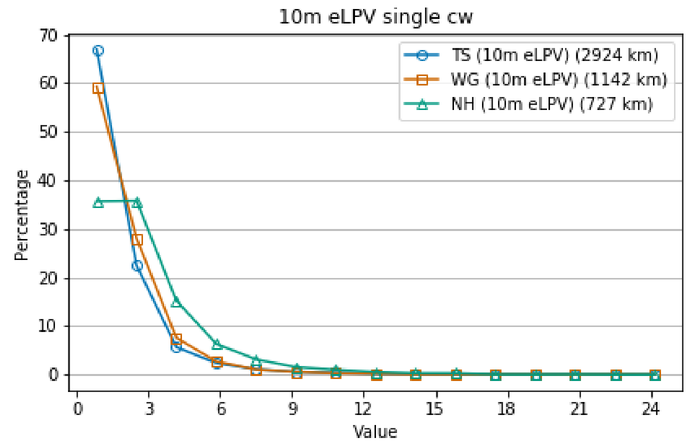


	TS	WG	NH	RWS
TS	Not assessed			
WG	Not assessed	N/A	Negl	Not assessed
NH		Negl	N/A	
RWS		Not assessed		
Mean		13.59	14.50	
5th %tile		11.58	9.556	
95th %tile		14.41	34.02	

10m eLPV benchmarking by carriageway type



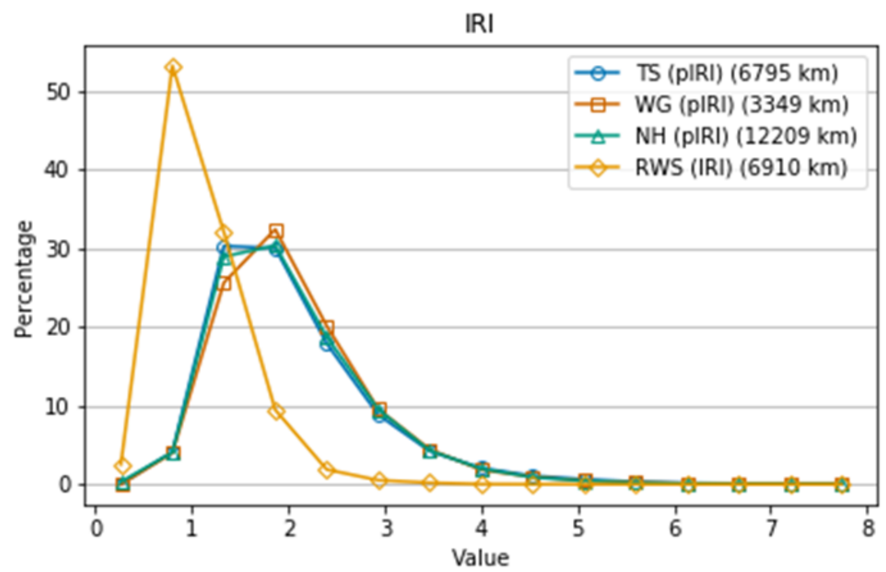


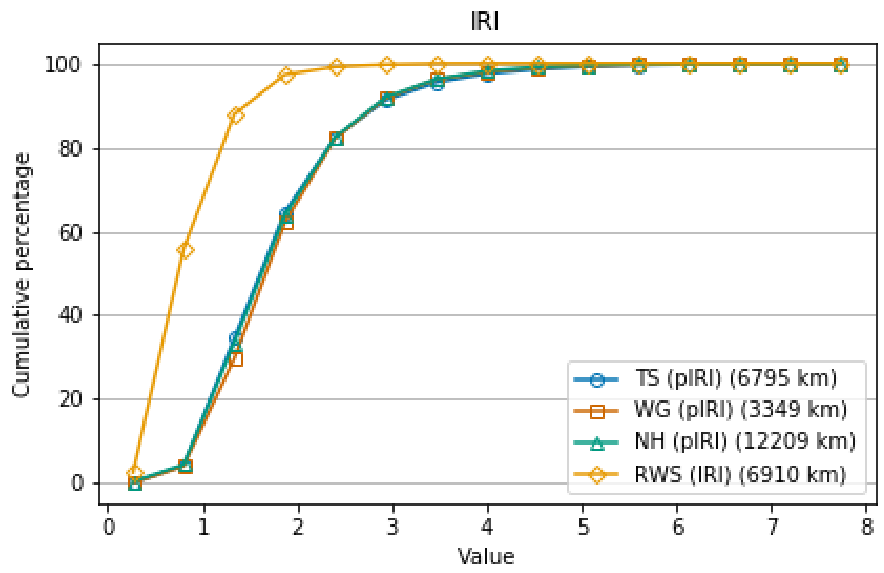


Mean for:	TS	WG	NH	RWS
Motorway	1.292	1.112	1.738	Not assessed
Dual CW	1.390	1.125	2.126	
Single CW	1.745	1.944	2.908	

D.3 IRI

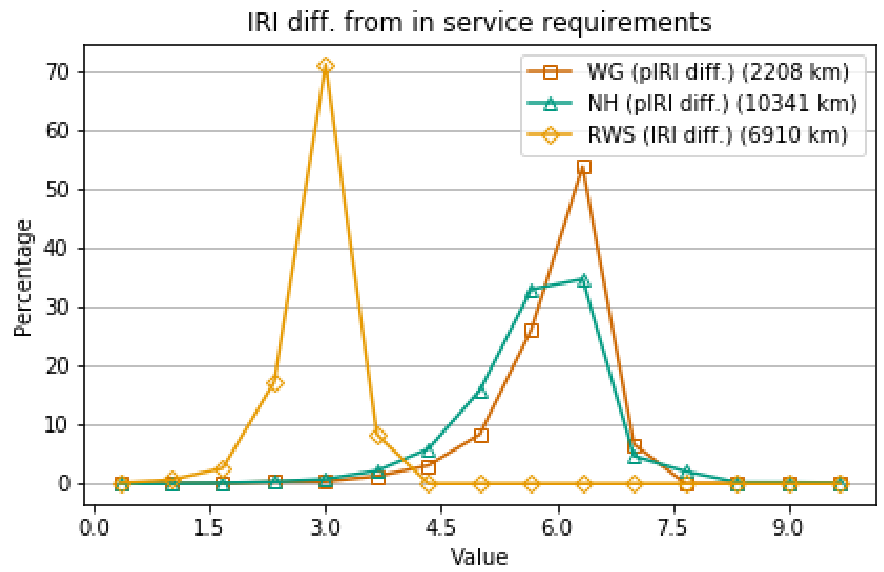
IRI benchmarking

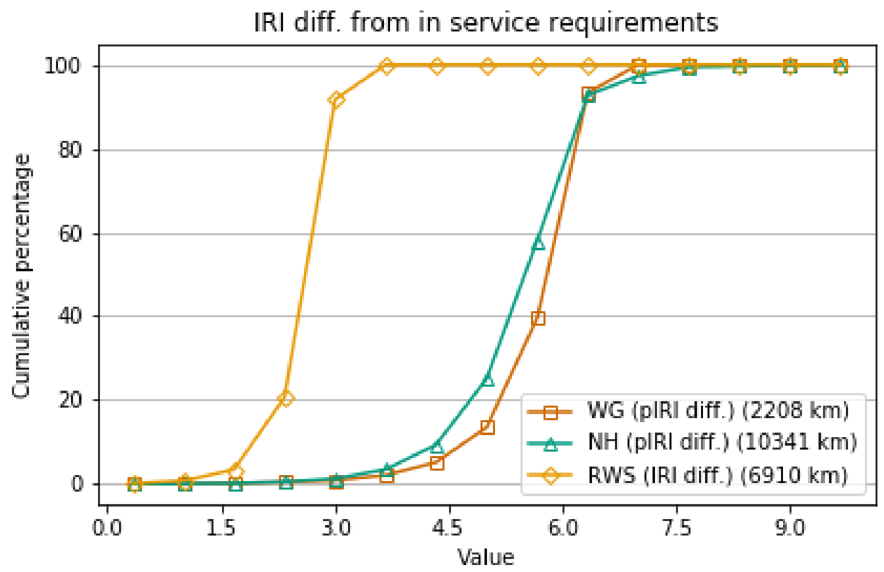




	TS	WG	NH	RWS
TS	N/A	Negl.	Negl.	Large
WG	Negl.	N/A	Negl.	Large
NH	Negl.	Negl.	N/A	Large
RWS	Large	Large	Large	N/A
Mean	2.045	2.074	2.03	1.092
5th %tile	1.093	1.123	1.087	0.600
95th %tile	3.768	3.709	3.618	1.936

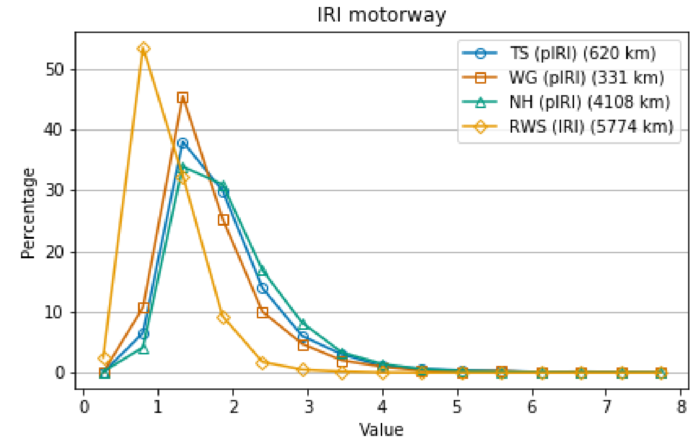
IRI difference from in service requirements

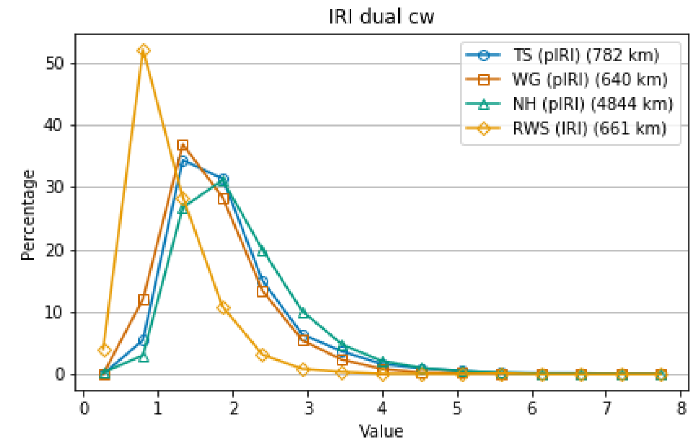


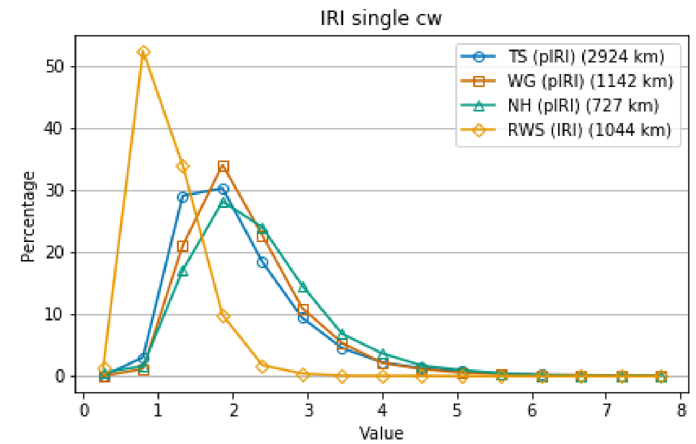


	TS	WG	NH	RWS
TS			Not Assessed	
WG		N/A	Small	Large
NH		Small	N/A	Large
RWS	Not Assessed	Large	Large	N/A
Mean		5.968	5.758	2.906
5th %tile		4.582	4.120	2.100
95th %tile		6.698	6.900	3.400

IRI benchmarking by carriageway type



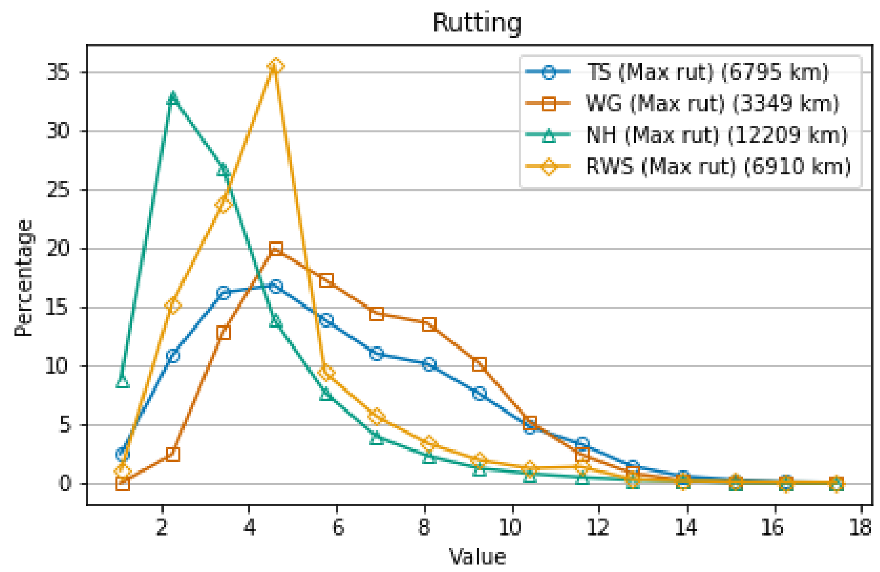


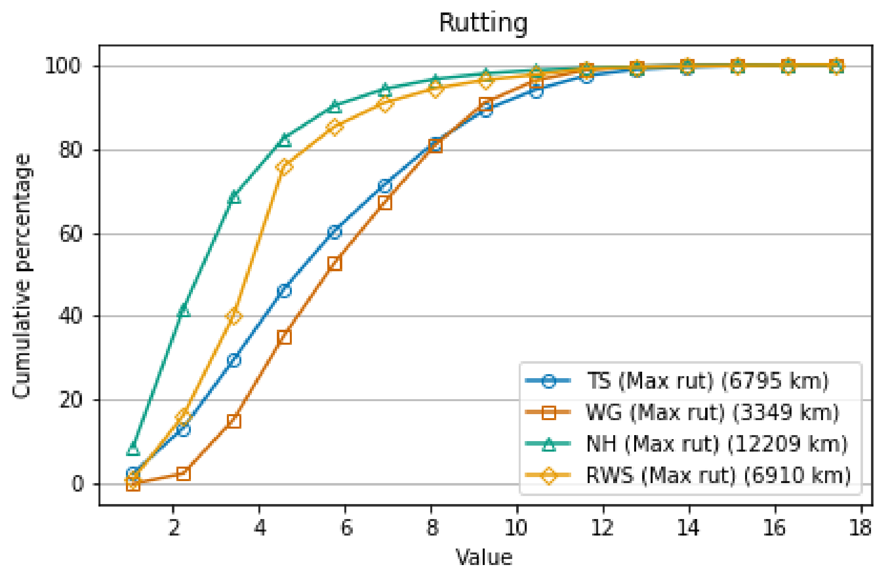


Mean for:	TS	WG	NH	RWS
Motorway	1.864	1.696	1.934	1.088
Dual CW	1.943	1.752	2.081	1.120
Single CW	2.095	2.196	2.323	1.105

D.4 Rutting

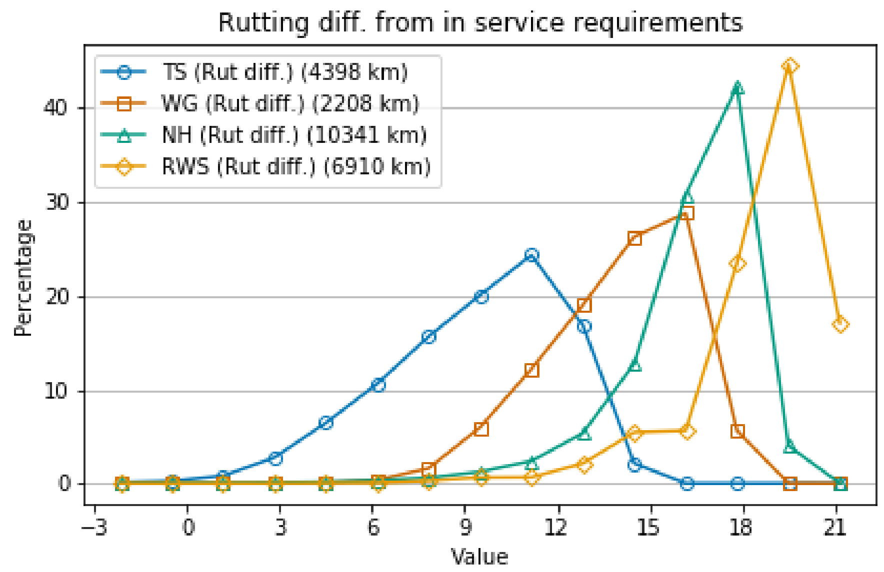
Rutting benchmarking

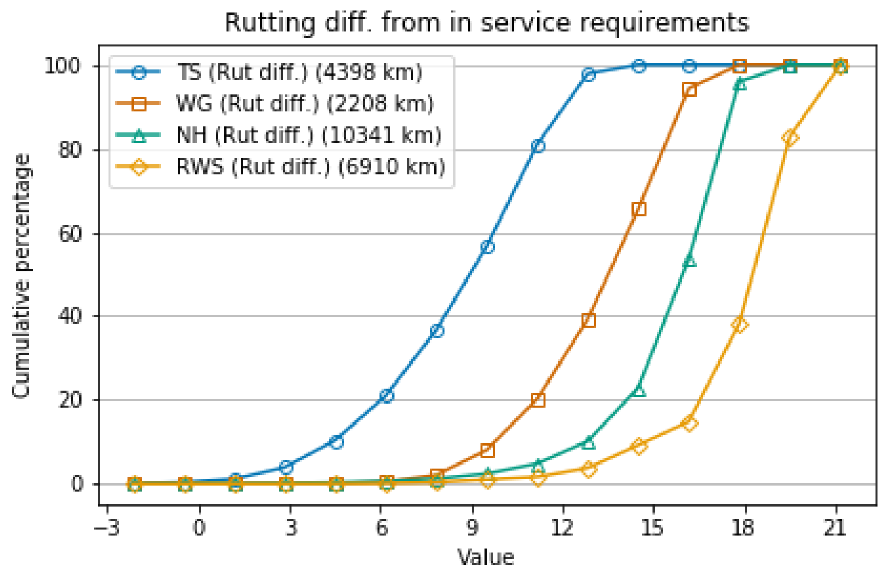




	TS	WG	NH	RWS
TS	N/A	Small	Large	Med.
WG	Small	N/A	Large	Large
NH	Large	Large	N/A	Small
RWS	Med.	Large	Small	N/A
Mean	5.938	6.443	3.685	4.451
5th %tile	2.000	3.100	1.427	2.000
95th %tile	11.10	10.50	7.854	9.000

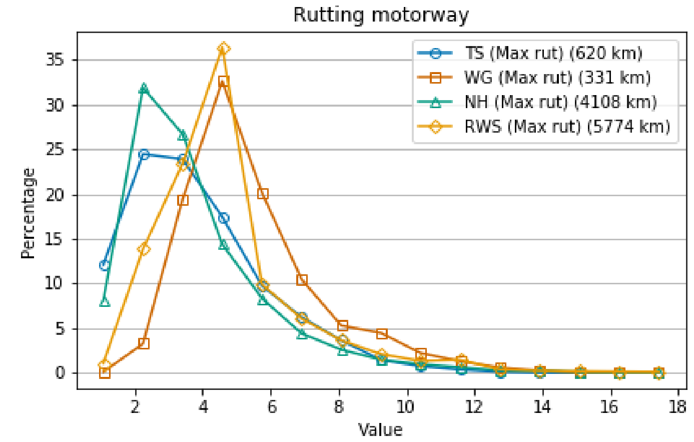
Rutting difference from in service requirements

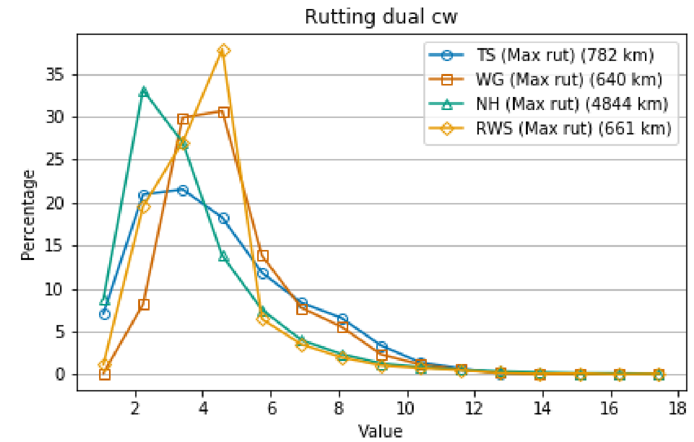


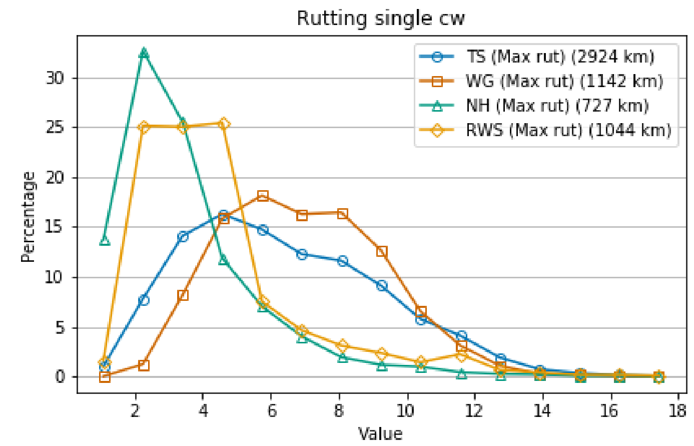


	TS	WG	NH	RWS
TS	N/A	Large	Large	Large
WG	Large	N/A	Large	Large
NH	Large	Large	N/A	Large
RWS	Large	Large	Large	N/A
Mean	9.320	13.98	16.30	18.57
5th %tile	4.100	9.700	12.00	14.00
95th %tile	13.10	17.00	18.56	21.00

Rutting benchmarking by carriageway type



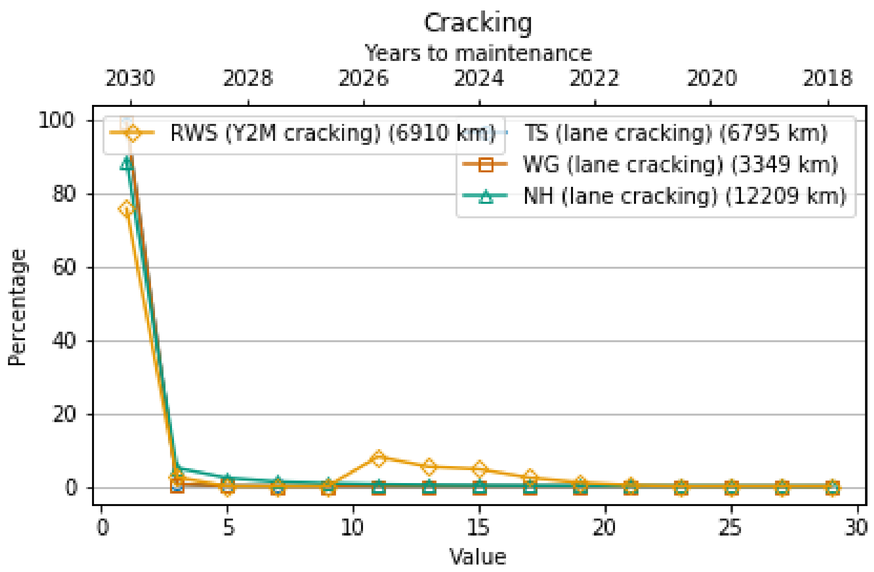


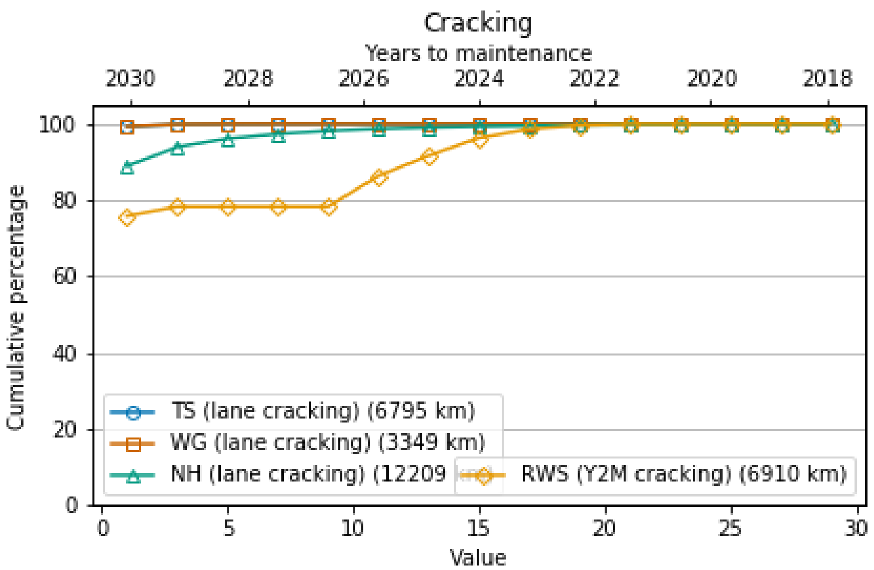


Mean for:	TS	WG	NH	RWS
Motorway	3.820	5.415	3.764	4.523
Dual CW	4.432	4.776	3.697	3.961
Single CW	6.407	6.943	3.522	4.244

D.5 Cracking

Cracking benchmarking





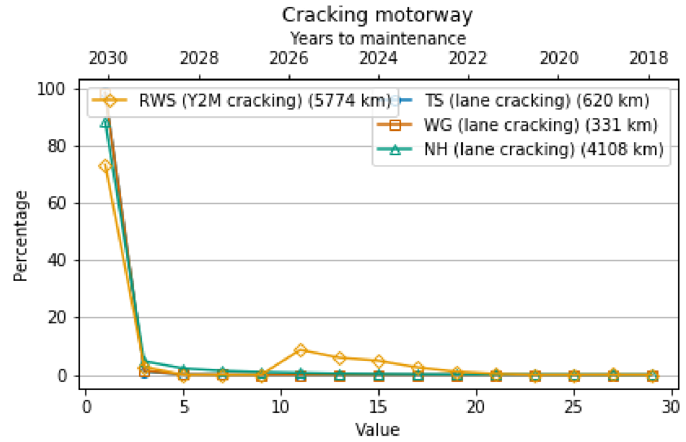
	TS	WG	NH	RWS
TS	N/A	Negl.	Large	
WG	Negl.	N/A	Large	
NH	Large	Large	N/A	
RWS	Not Assessed			Not Assessed
Mean	0.195	0.181	0.888	
5th %tile	0	0	0	
95th %tile	0.830	0.831	4.700	

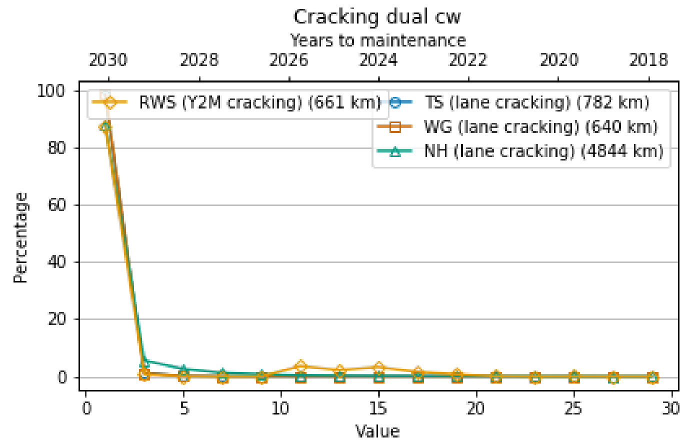
Cracking difference from in service requirements

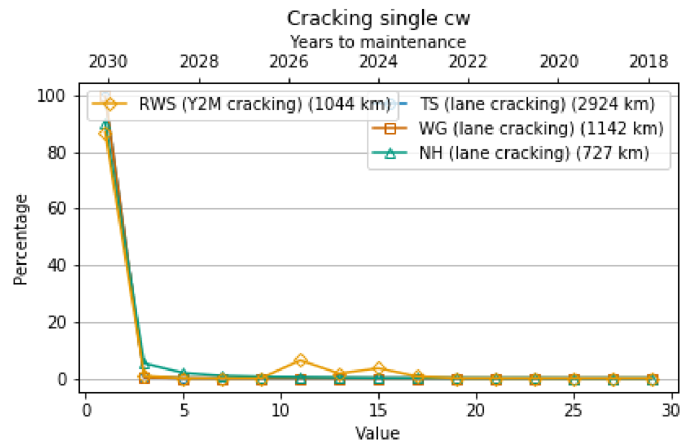
Distributions not appropriate.

Statistics not appropriate.

Cracking benchmarking by carriageway type



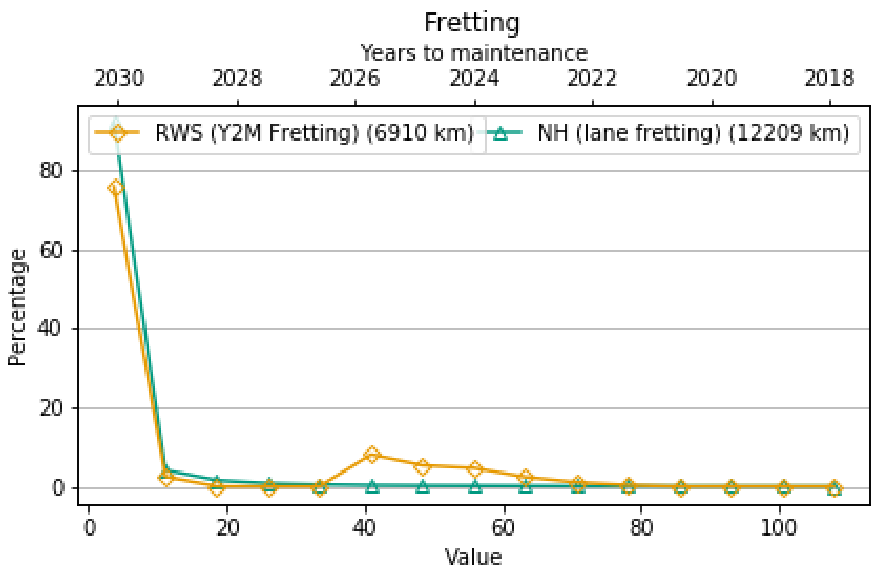


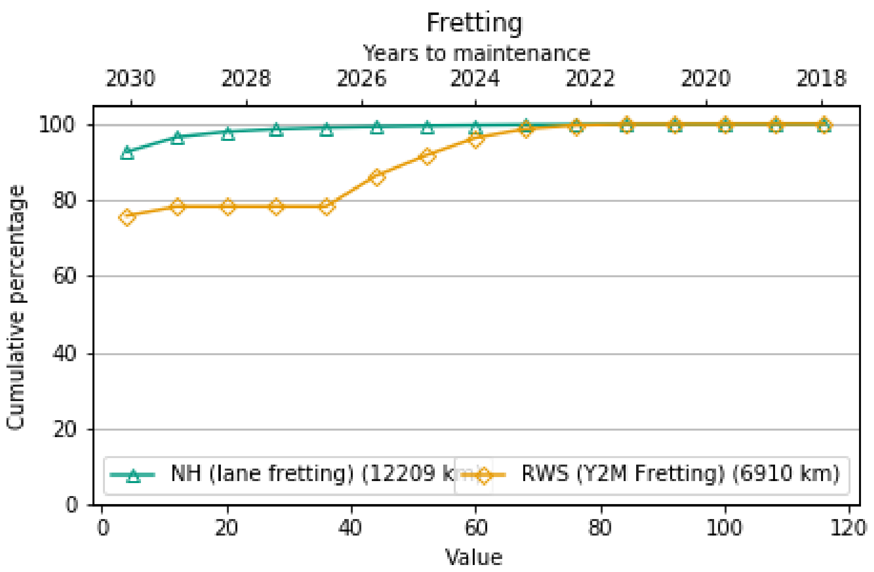


Mean for:	TS	WG	NH	RWS
Motorway	0.150	0.223	0.984	
Dual CW	0.203	0.147	0.879	Not Assessed
Single CW	0.196	0.176	0.687	

D.6 Fretting

Fretting benchmarking





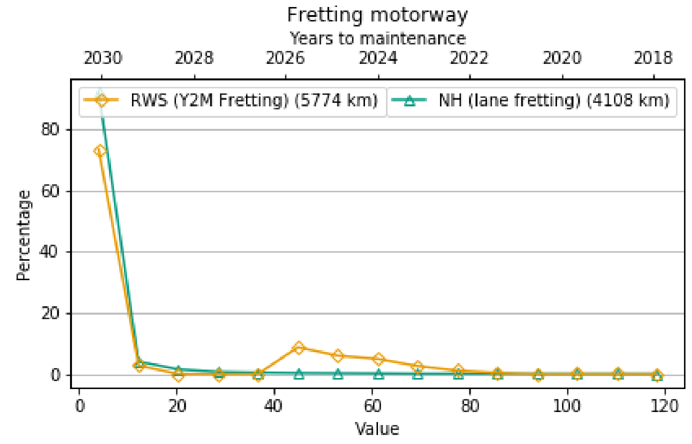
	TS	WG	NH	RWS
TS	Not Assessed			
WG				
NH				
RWS				
Mean	Not Assessed		2.609	Not Assessed
5th %tile			0.000	
95th %tile			19.73	

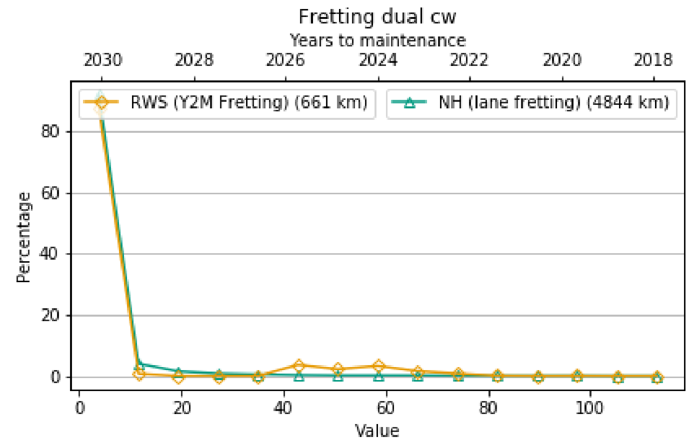
Fretting difference from in service requirements

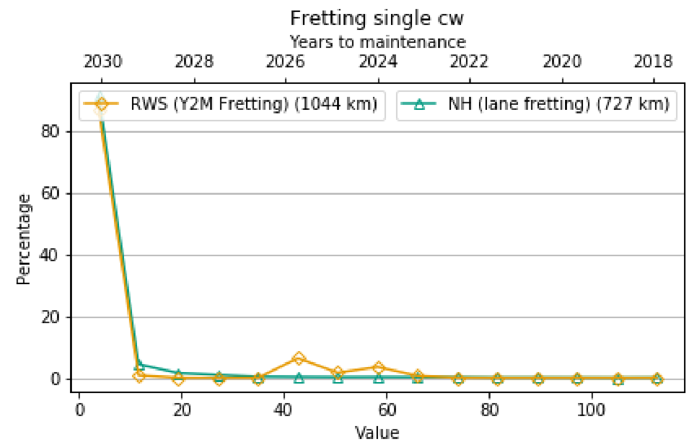
Distributions not appropriate.

Statistics not appropriate.

Fretting benchmarking by carriageway type



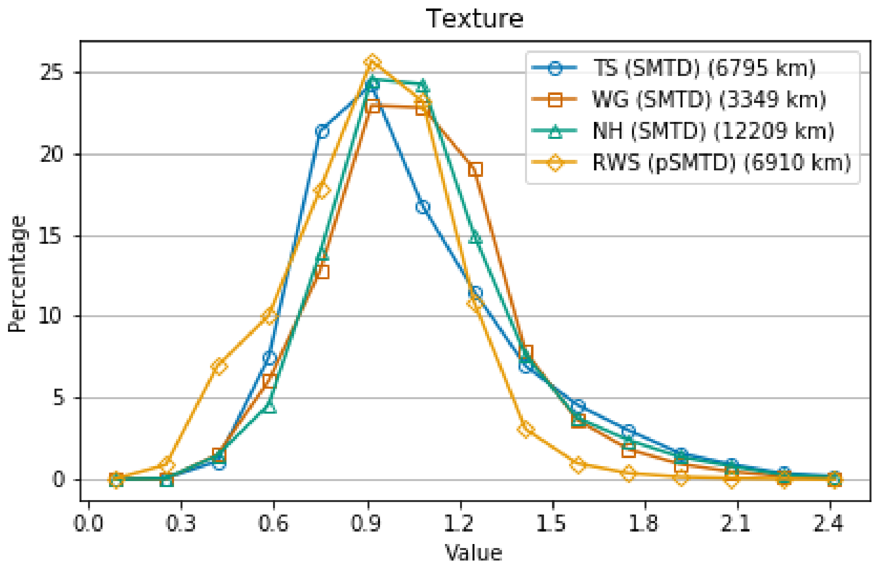


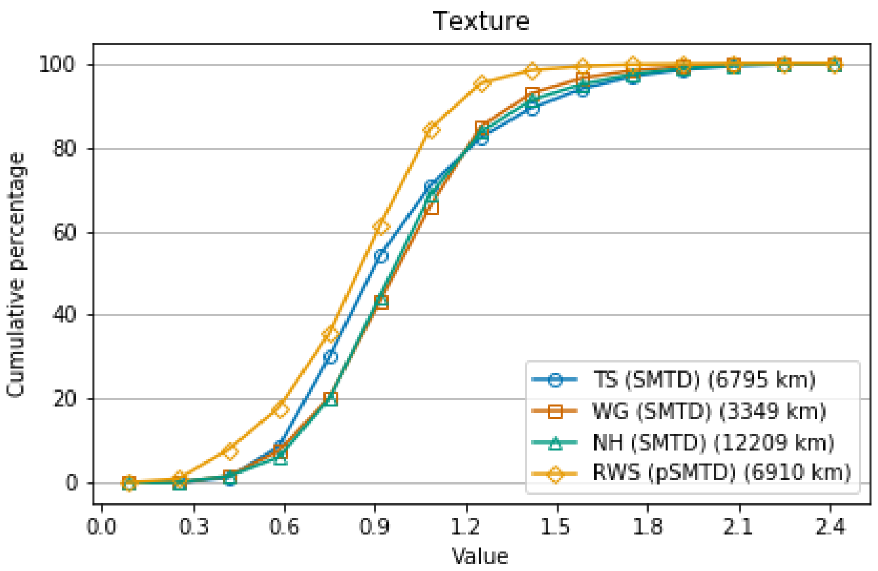


Mean for:	TS	WG	NH	RWS
Motorway	Not Assessed		2.862	Not Assessed
Dual CW			2.751	
Single CW			2.969	

D.7 Texture depth

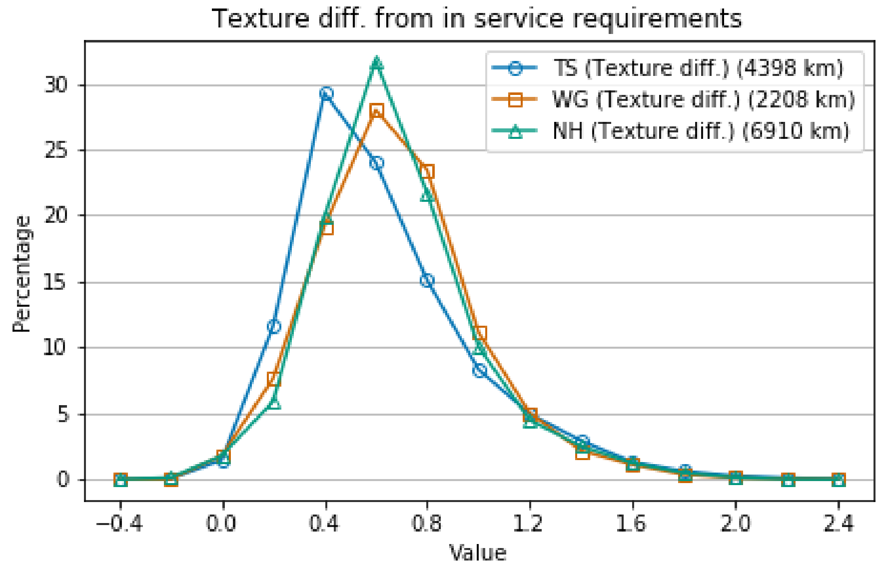
Texture depth benchmarking

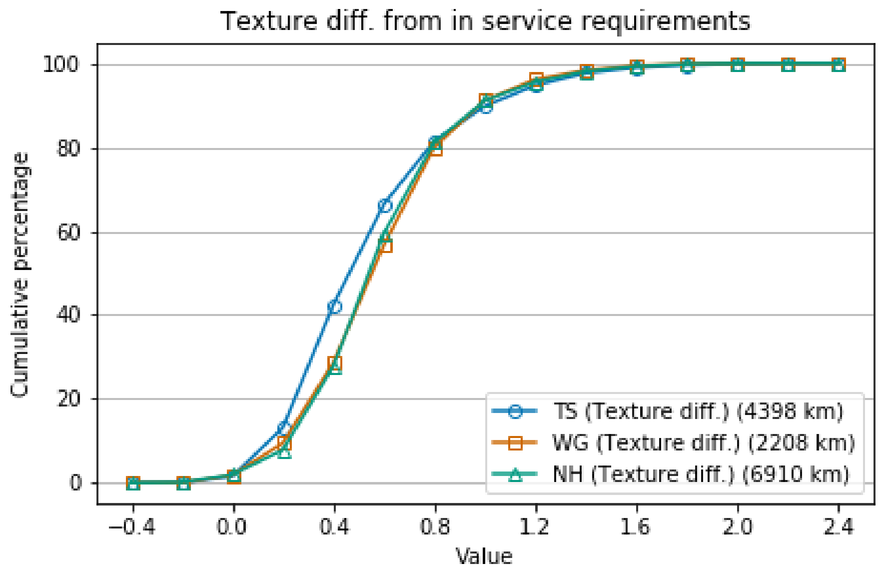




	TS	WG	NH	RWS
TS	N/A	Negl.	Negl.	Small
WG	Negl.	N/A	Negl.	Med.
NH	Negl.	Negl.	N/A	Med.
RWS	Small	Med.	Med	N/A
Mean	1.044	1.066	1.073	0.915
5th %tile	0.605	0.595	0.632	0.446
95th %tile	1.707	1.555	1.664	1.331

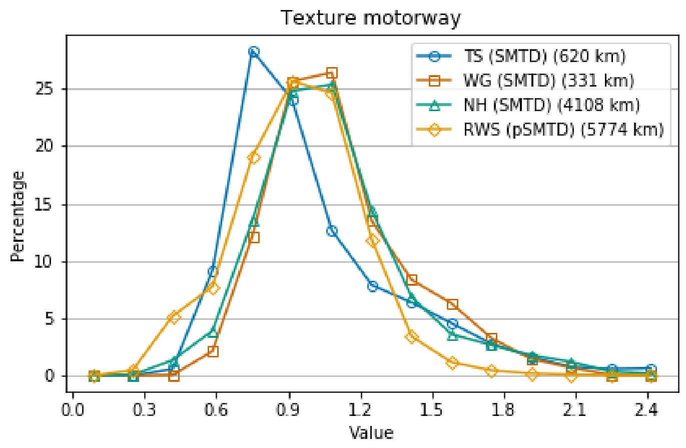
Texture depth difference from in service requirements

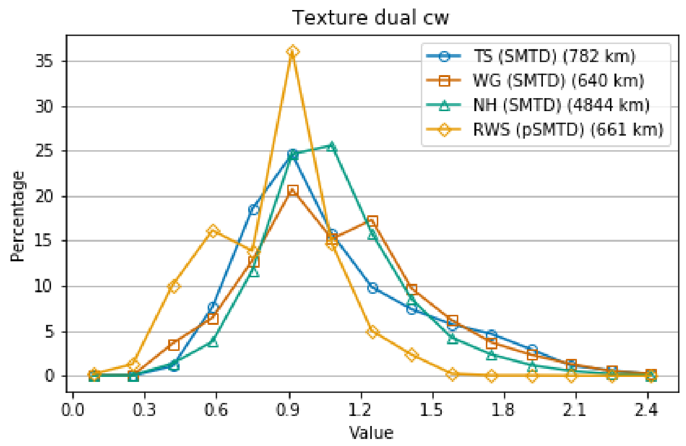


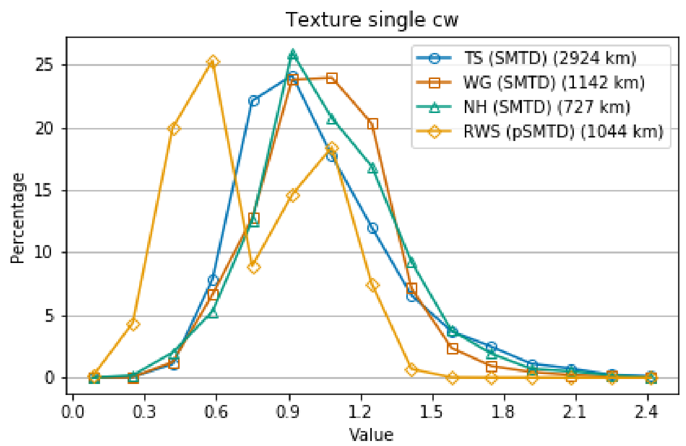


	TS	WG	NH	RWS
TS	N/A	Negl.	Negl.	
WG	Negl.	N/A	Negl.	
NH	Negl.	Negl.	N/A	
RWS	Not assessed			Not Assessed
Mean	0.630	0.678	0.676	
5th %tile	0.200	0.197	0.207	
95th %tile	1.243	1.208	1.247	

Texture depth benchmarking by carriageway type



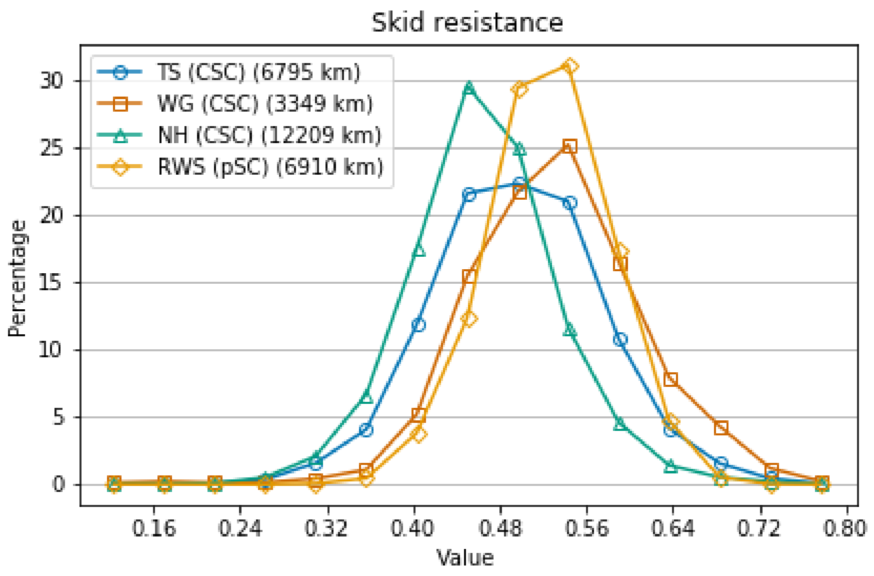


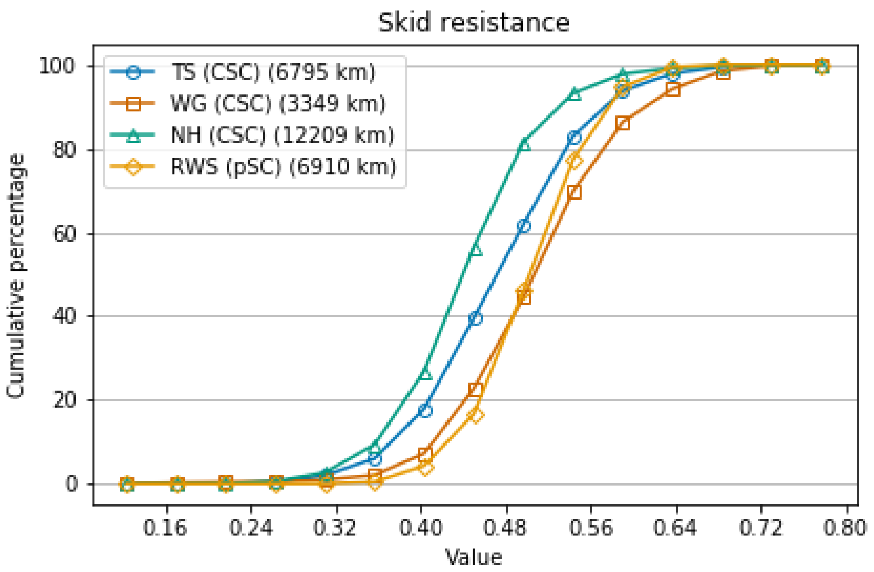


Mean for:	TS	WG	NH	RWS
Motorway	1.018	1.115	1.085	0.943
Dual CW	1.084	1.108	1.085	0.830
Single CW	1.022	1.041	1.060	0.747

D.8 Skid resistance

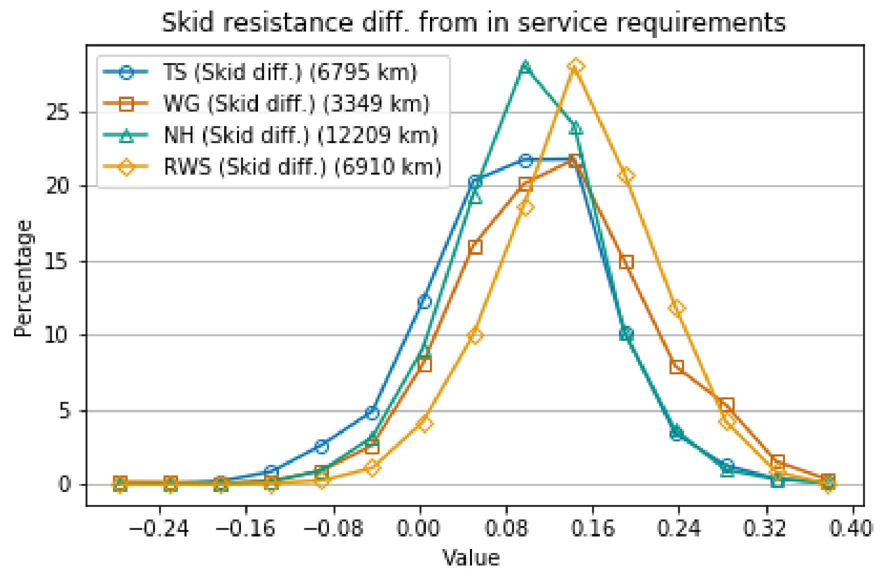
Skid resistance benchmarking

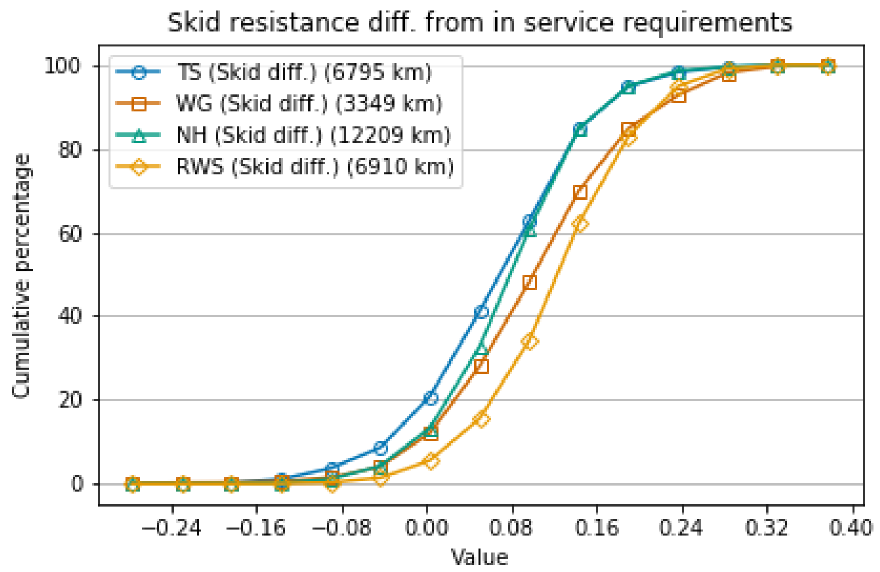




	TS	WG	NH	RWS
TS	N/A	Small	Small	Small
WG	Small	N/A	Large	Negl.
NH	Small	Large	N/A	Large
RWS	Small	Negl.	Large	N/A
Mean	0.495	0.529	0.465	0.525
5th %tile	0.370	0.410	0.356	0.431
95th %tile	0.649	0.688	0.601	0.635

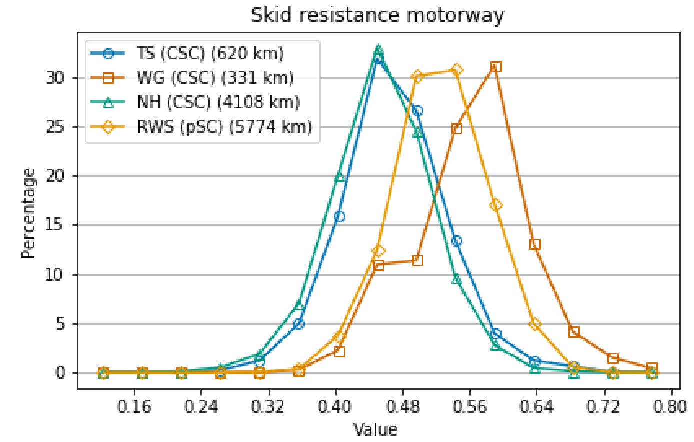
Skid resistance difference from in service requirements

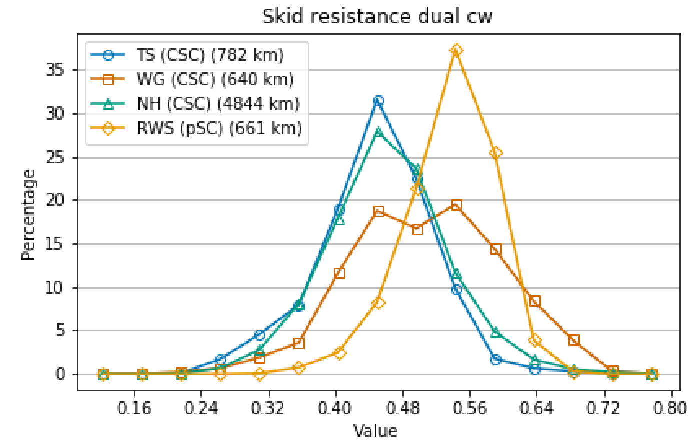


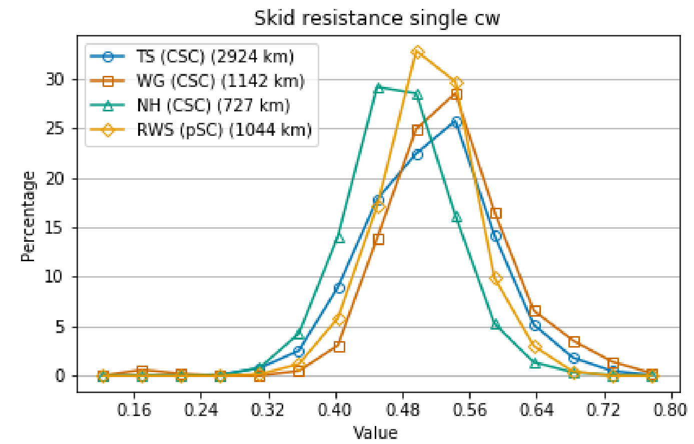


	TS	WG	NH	RWS
TS	N/A	Small	Negl.	Med.
WG	Small	N/A	Small	Small
NH	Negl.	Small	N/A	Med.
RWS	Med.	Small	Med.	N/A
Mean	0.088	0.123	0.101	0.148
5th %tile	-0.060	-0.022	-0.018	0.023
95th %tile	0.246	0.302	0.240	0.281

Skid resistance benchmarking by carriageway type







Mean for:	TS	WG	NH	RWS
Motorway	0.469	0.560	0.456	0.525
Dual CW	0.447	0.507	0.463	0.537
Single CW	0.511	0.532	0.478	0.510

Appendix E National benchmarking summary statistics

Stat	Authority	Length (km)	Mean	5th %tile	95th %tile	St.dev.	Skew	kurtosis
			3m eLPV					
3m eLPV	**TS**	6,794	0.518	0.115	1.688	0.692	7.65	167.8
	WG	3,349	0.489	0.117	1.508	0.627	16.66	993.8
	NH	12,208	0.459	0.109	1.377	0.520	5.060	59.39
3m eLPV diff.[13]	**WG**	2,207	4.030	3.298	4.308	0.688	-29.39	1547
	NH	10,340	4.054	3.053	5.108	0.655	0.140	26.26
3m eLPV mot.[14]	**TS**	619	0.445	0.103	1.330	0.685	8.061	104.1
	WG	330	0.370	0.092	1.102	0.688	29.39	1547
	NH	4,107	0.423	0.111	1.281	0.463	4.801	47.16
3m eLPV d-cw.[15]	**TS**	781	0.501	0.113	1.645	0.691	6.053	66.41
	WG	640	0.365	0.083	1.050	0.440	7.13	96.83
	NH	4,844	0.472	0.117	1.478	0.518	4.156	33.12
3m eLPV s-cw.[16]	**TS**	2,924	0.539	0.122	1.706	0.755	8.253	144.0
	WG	1,142	0.529	0.142	1.534	0.622	7.904	133.0
	NH	727	0.564	0.138	1.866	0.600	4.313	43.36
			10m eLPV					
10m eLPV	**TS**	6,794	1.603	0.369	5.116	1.785	5.927	87.19
	WG	3,349	1.699	0.41	5.198	1.835	15.49	884.4
	NH	12,208	2.036	0.486	5.568	1.868	4.03	40.41
10m eLPV diff.	**WG**	2,207	13.59	11.58	14.41	1.396	-18.36	763.5
	NH	10,340	14.50	9.556	34.02	6.012	2.641	9.486
10m eLPV mot.	**TS**	619	1.292	0.332	3.381	1.648	9.262	165.5
	WG	330	1.112	0.289	3.116	1.396	18.36	763.5
	NH	4,107	1.738	0.475	4.779	1.514	4.099	38.29
10m eLPV d-cw.	**TS**	781	1.390	0.357	4.033	1.602	5.836	59.21
	WG	640	1.125	0.283	3.015	1.036	5.15	80.59

[13] For ‘diff.’ read ‘difference from in service requirements’.

[14] For ‘mot’ read ‘motorway’.

[15] For ‘d-cw.’ read ‘dual carriageway’.

[16] For ‘s-cw.’ read ‘single carriageway’

Stat	Authority	Length (km)	Mean	5th %tile	95th %tile	St.dev.	Skew	kurtosis
10m eLPV s-cw.	NH	4,844	2.126	0.553	5.833	1.818	3.35	25.61
	TS	2,924	1.745	0.402	5.426	1.948	5.171	56.82
	WG	1,142	1.944	0.523	5.548	2.243	23.46	1,370
	NH	727	2.908	0.717	8.181	2.49	2.891	18.09
IRI								
IRI	TS	6,794	2.045	1.093	3.838	0.861	1.96	10.29
	WG	3,349	2.074	1.123	3.763	0.818	2.038	13.89
	NH	12,208	2.03	1.087	3.601	0.794	1.388	6.719
	RWS	6,909	1.092	0.6	1.9	0.422	1.694	8.223
IRI diff.	WG	2,207	5.968	4.582	6.698	0.708	-3.199	36.15
	NH	10,340	5.758	4.120	6.900	0.856	-0.515	6.46
	RWS	7,493	2.906	2.100	3.400	0.424	-1.793	9.519
IRI mot.	TS	619	1.864	1.032	3.312	0.811	2.798	19.06
	WG	330	1.696	0.966	3.082	0.708	3.199	36.15
	NH	4,107	1.934	1.099	3.443	0.724	1.457	6.753
	RWS	5,774	1.088	0.600	1.900	0.413	1.627	7.654
IRI d-cw.	TS	781	1.943	1.071	3.578	0.829	2.139	10.71
	WG	640	1.752	0.925	3.094	0.702	1.781	9.522
	NH	4,844	2.081	1.150	3.727	0.793	1.334	6.225
	RWS	661	1.120	0.600	2.100	0.53	2.449	14.76
IRI s-cw.	TS	2,924	2.095	1.13	3.873	0.888	1.953	9.768
	WG	1,142	2.196	1.273	3.835	0.824	2.04	11.9
	NH	727	2.323	1.274	4.138	0.875	1.07	5.237
	RWS	1,044	1.105	0.6	1.9	0.407	1.645	8.466
Rutting								
Rutting	TS	6,794	5.936	2.000	11.1	2.928	0.764	3.698
	WG	3,349	6.45	3.1	10.5	2.384	0.607	3.398
	NH	12,208	3.685	1.427	7.854	2.159	2.13	10.37
	RWS	6,909	4.451	2.000	9.000	2.275	1.632	7.237
Rutting diff.	TS	4,398	9.320	4.100	13.10	2.897	-0.778	3.668
	WG	2,207	13.98	9.700	17.00	2.334	-0.766	3.534
	NH	10,340	16.30	12.00	18.56	2.183	-2.121	10.35
	RWS	7,493	18.57	14.00	21.00	2.297	-1.638	7.153

Stat	Authority	Length (km)	Mean	5th %tile	95th %tile	St.dev.	Skew	kurtosis
Rutting mot.	TS	619	3.820	1.100	7.600	2.051	0.983	4.02
	WG	330	5.415	3.000	9.5	2.025	1.298	4.924
	NH	4,107	3.764	1.474	8.02	2.164	1.923	8.902
	RWS	5,774	4.523	2.000	9.000	2.27	1.582	7.008
Rutting d-cw.	TS	781	4.432	1.500	8.700	2.286	0.793	3.238
	WG	640	4.776	2.600	8.300	1.797	1.268	4.799
	NH	4,844	3.697	1.455	8.028	2.205	2.280	11.41
	RWS	661	3.961	2.000	7.000	1.919	2.186	13.37
Rutting s-cw.	TS	2,924	6.407	2.400	11.40	2.916	0.689	3.615
	WG	1,142	6.943	3.500	10.80	2.331	0.478	3.556
	NH	727	3.522	1.232	7.922	2.244	2.295	11.52
	RWS	1,044	4.244	2.000	10.00	2.586	1.700	6.253
				Cracking				
Cracking	TS	6,794	0.195	0	0.83	0.412	8.718	189.8
	WG	3,349	0.181	0	0.8313	0.366	5.89	73.25
	NH	12,208	0.888	0	4.7	2.678	5.992	51.8
	RWS	6,909	2029	2024	2030	2.244	-1.639	4.229
Cracking mot.	TS	619	0.150	0	0.71	0.456	6.518	64.89
	WG	330	0.223	0	1.2	0.479	3.826	25.97
	NH	4,107	0.984	0	5.4	2.997	5.779	47.18
	RWS	5,774	2029	2024	2030	2.325	-1.504	3.803
Cracking d-cw.	TS	781	0.203	0	0.9	0.492	6.642	77.55
	WG	640	0.147	0	0.75	0.435	6.095	51.74
	NH	4,844	0.879	0	4.7	2.512	6.023	54.52
	RWS	661	2029	2024	2030	1.811	-2.681	8.823
Cracking s-cw.	TS	2,924	0.196	0	0.785	0.388	10.31	232.1
	WG	1,142	0.176	0	0.79	0.291	3.481	21.47
	NH	727	0.687	0	3.4	1.998	6.834	75.47
	RWS	1,044	2029	2025	2030	1.637	-2.516	7.822
				Fretting				
Fretting	NH	12,208	2.609	0	12.07	8.56	9.241	151.9
	RWS	6,909	2029	2024	2030	2.244	-1.639	4.229
Fretting mot.	NH	4,107	2.862	0	15.33	9.168	9.444	170.5
	RWS	5,774	2029	2024	2030	2.325	-1.504	3.803

Stat	Authority	Length (km)	Mean	5th %tile	95th %tile	St.dev.	Skew	kurtosis
Fretting d-cw.	**NH**	4,844	2.751	0	14.71	8.854	8.128	104.7
	RWS	661	2029	2024	2030	1.811	-2.681	8.823
Fretting s-cw.	**NH**	727	2.969	0.000	17.05	9.433	7.385	81.42
	RWS	1,044	2029	2025	2030	1.637	-2.516	7.822
Texture depth								
Texture depth	**TS**	6,794	1.044	0.605	1.707	0.344	1.102	4.607
	WG	3,349	1.066	0.595	1.555	0.294	0.612	4.175
	NH	12,208	1.073	0.632	1.664	0.308	0.887	4.547
	RWS	6,909	0.915	0.4463	1.331	0.27	0.134	3.793
Texture depth diff.	**TS**	4,398	0.630	0.200	1.243	0.343	1.131	4.629
	WG	2,207	0.678	0.1965	1.208	0.31	0.654	4.068
	NH	10,340	0.676	0.207	1.247	0.308	0.809	4.508
Texture depth mot.	**TS**	619	1.018	0.610	1.696	0.372	1.495	5.538
	WG	330	1.115	0.717	1.68	0.29	0.905	3.736
	NH	4,107	1.085	0.658	1.724	0.32	1.049	4.815
	RWS	5,774	0.943	0.4876	1.347	0.261	0.261	4.123
Texture depth d-cw.	**TS**	781	1.084	0.607	1.776	0.372	0.968	3.638
	WG	640	1.108	0.537	1.792	0.371	0.569	3.324
	NH	4,844	1.085	0.652	1.628	0.293	0.74	4.307
	RWS	661	0.83	0.397	1.231	0.253	-0.225	3.781
Texture depth s-cw.	**TS**	2,924	1.022	0.614	1.578	0.322	1.095	4.705
	WG	1,142	1.041	0.599	1.457	0.264	0.362	3.859
	NH	727	1.060	0.608	1.564	0.297	0.537	3.902
	RWS	1,044	0.747	0.347	1.215	0.293	0.209	1.895
Skid resistance								
Skid resistance	**TS**	6,794	0.495	0.370	0.630	0.077	0.057	3.211
	WG	3,349	0.529	0.410	0.670	0.08	-0.202	4.753
	NH	12,208	0.465	0.356	0.584	0.068	0.218	3.981
	RWS	6,909	0.525	0.4313	0.614	0.055	-0.092	3.038
Skid resistance diff.	**TS**	6,794	0.088	-0.060	0.218	0.081	-0.155	3.48
	WG	3,349	0.123	-0.022	0.270	0.089	-0.193	4.266
	NH	12,208	0.101	-0.018	0.215	0.069	0.036	3.749
	RWS	7,493	0.145	0.023	0.260	0.071	-0.168	3.135
Skid resistance mot.	**TS**	619	0.469	0.370	0.570	0.062	0.218	3.969

Stat	Authority	Length (km)	Mean	5th %tile	95th %tile	St.dev.	Skew	kurtosis
	WG	330	0.560	0.440	0.670	0.070	-0.055	3.165
	NH	4,107	0.456	0.356	0.553	0.060	-0.063	3.890
	RWS	5,774	0.525	0.432	0.615	0.055	-0.040	2.991
	TS	781	0.447	0.330	0.550	0.068	-0.167	3.735
Skid resistance d-cw.	**WG**	640	0.507	0.360	0.650	0.089	-0.130	2.758
	NH	4,844	0.463	0.349	0.587	0.072	0.211	3.702
	RWS	661	0.537	0.4384	0.6106	0.052	-0.605	3.716
	TS	2,924	0.511	0.394	0.630	0.073	-0.006	3.214
Skid resistance s-cw.	**WG**	1,142	0.532	0.430	0.660	0.075	-0.374	6.630
	NH	727	0.478	0.379	0.587	0.061	0.190	3.482
	RWS	1,044	0.510	0.4106	0.5987	0.055	-0.096	3.362

Appendix F Approach to the deeper dive analysis

F.1 Stage 1: Selection of additional explanatory variables

F.1.1 Stage 1.1: Selection of additional explanatory variables, assess the distribution of additional explanatory variables.

The selection of additional explanatory variables through which the deeper dive was carried out required the distribution of each explanatory variable to be different for each of the NRAs; if this were not the case then it was considered that the use of that variable would not add value to the deeper dive. To identify the additional explanatory variables which demonstrated differences in distributions between the NRAs, histograms and bar charts showing the distribution of each additional explanatory variable for each NRA (Figure F-1 to Figure F-5) were produced.

F.1.2 Material age

Figure F-1 presents the distribution of surface ages for each of the NRAs with the x-axis representing the age of materials in days and the y-axis the percentage of the network. Here it can be observed that the RWS network appears to be substantially younger than the UK networks. The distribution ages on the WG network differ from the pattern observed on the other networks (a continual decline in prevalence with age) as it demonstrates a peak in ages at around 7500 days.

Given the difference in distribution of ages for each of the NRAs, the inclusion of age in the deeper dive was considered of value.

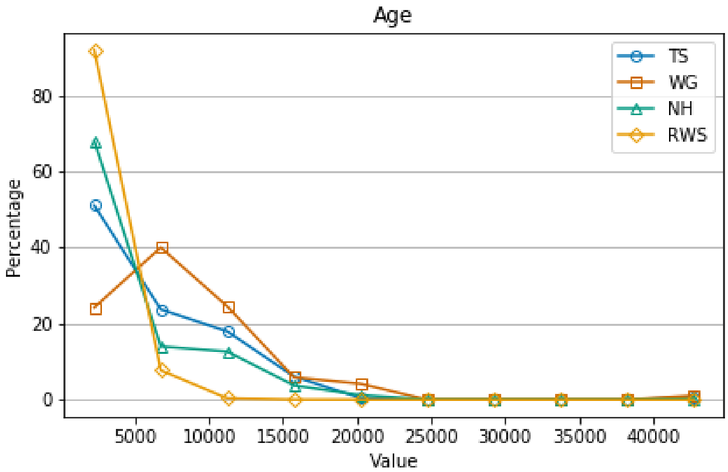


Figure F-1 Distribution of surface ages for all NRAs

F.1.2.1 Operational environment

Figure F-2 shows the distribution of operational environment categories as a bar chart; data were not available for the RWS network. Here it can be observed that almost 100% of the

TS and NH networks are in rural environments and approximately 15% of the WG network is in urban environments.

Given that there is little difference in the distribution of operational environments for the UK networks, and there are no data available for the RWS network, it is unlikely that operational environment would be a valuable inclusion to the deeper dive.

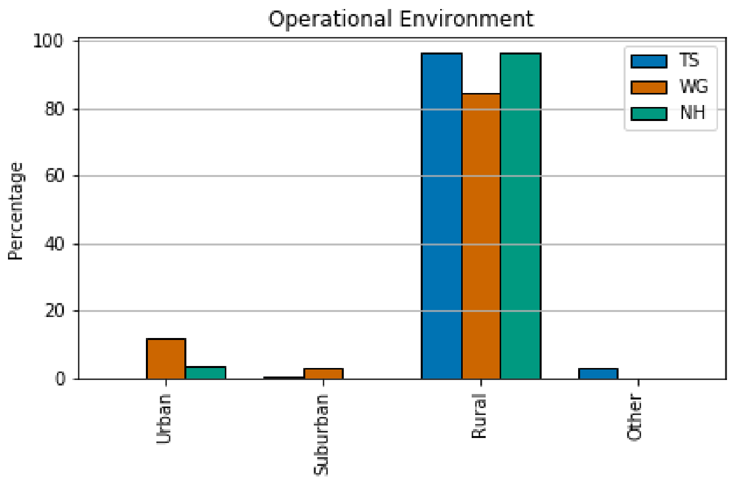


Figure F-2 Distribution of operational environments for the UK NRAs

F.1.2.2 Material type

Figure F-3 presents the distribution of material types for all NRAs as a bar chart. The abbreviations used in the x-axis labels refer to the following material categories:

- TSCS: Thin Surface course systems,
- HRA: Hot Rolled Asphalts,
- SD: Surface Dressings,
- HFS: High Friction Surfacings,
- Asph.: Asphalt materials for which could not be assigned to a more specific category
- Conc. All non-porous concrete materials
- P Asph.: Porous asphalts
- P Conc.: Porous concretes
- Unknown: materials definitions that were included in the data but which couldn't be assigned to one of the above material categories.
- Null: entries in the data for which no material type was given.

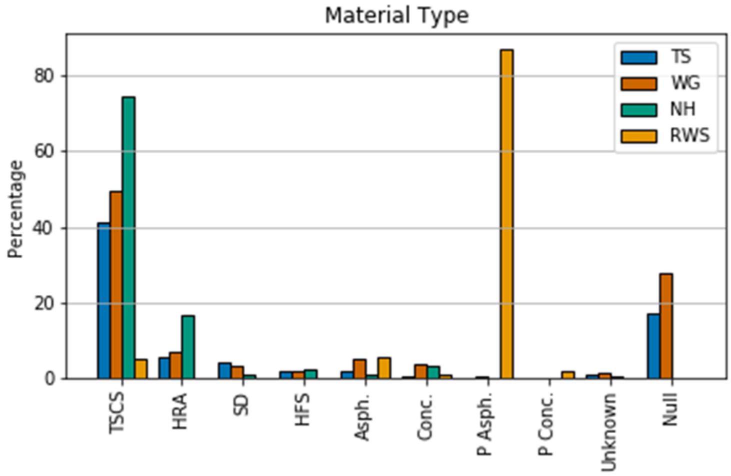


Figure F-3 Distribution of material types for all NRAs

Figure F-3 shows that the prevalence of TSCSs varies markedly for the NRAs. The NH network contains approximately 75% TSCS whereas the RWS network comprises approximately 2.5% TSCS. Approximately 90% of the RWS network is comprised of porous asphalt., whereas the UK networks contain no porous asphalt (or negligible amounts).

Given the large discrepancy in the composition of the NRAs in terms of material type the inclusion of material type in the deeper dive could offer insight.

F.1.2.3 Total HGV trafficking

Figure F-4 presents the distribution of the total amount of trafficking by heavy goods vehicles on each of the networks. Here it can be clearly seen that there is a difference in the total trafficking distributions between the NH and other NRAs and that this data could therefore offer insight as part of the deeper dive.

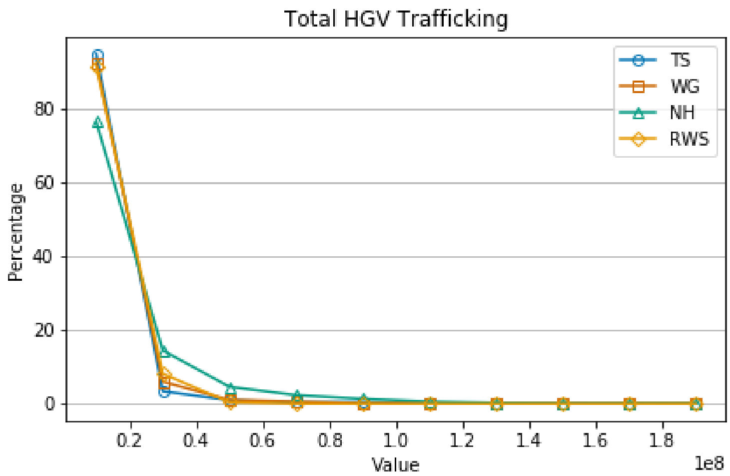


Figure F-4 Distribution of total trafficking for all NRAs

F.1.2.4 HGV trafficking rate

Figure F-5 shows the distribution of trafficking rates for each of the NRAs. Here there is an agreement in the shapes of the distributions for the NH and RWS networks, and the TS and WG networks. Furthermore there appears to be an offset in the lower trafficking rates between the TS and WG networks. HGV trafficking rate could therefore offer insight as part of the deeper dive.

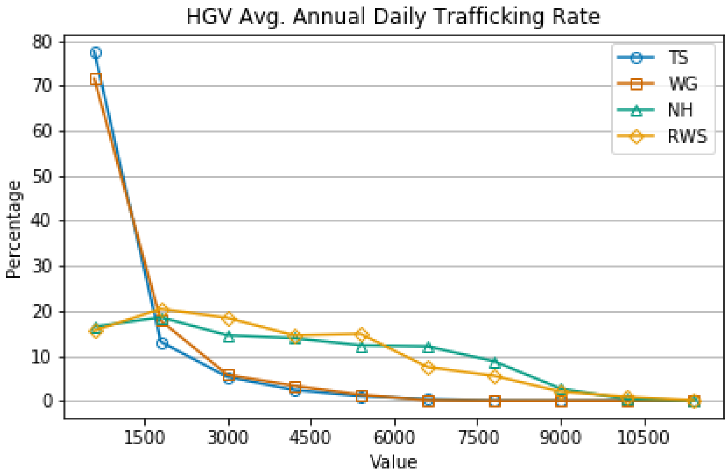


Figure F-5 Distribution of trafficking rates for all NRAs

F.1.3 Stage 1.2 Identify the additional explanatory variables that could have the most explanatory power, split the data by those variables and produce histograms.

In order to focus the deeper dive to those additional explanatory variables that have the most influence on the condition parameters assessed, a review was carried out to determine which of the additional explanatory variables accepted for the deeper dive would be assessed. The results of this review are presented in Table F-1.

Table F-1 Parameters selected for deeper dive analysis

Condition parameter	Additional explanatory variables	Notes
IRI	Material type	It is expected that material type will have some effect on longitudinal profile due to different methods of pavement application, and the different ways between which changes to pavement longitudinal profile would be expected between bituminous and cement based pavements.
	Total trafficking	The prevailing literature suggests that there is a fourth power relationship between HGV loading and road condition.
Rutting	Age	Rutting is generally caused by two modes; the deformation of a malleable road surface (for asphalt pavements), and erosion through tyre wear (studded tyres used in countries subject to extreme weather). With this in mind, it is expected that: • Exposure to weathering could affect the material in ways that would allow them to become more susceptible to rutting (Age) • Exposure to trafficking could increase rutting through the deformation of the road surface from HGVs (Total trafficking) • Asphalt materials should be more prone to rutting than concrete materials (Material type).
	Material type	
	Total trafficking	
Cracking	Age	The effects of weathering could make pavements more or less susceptible to cracking. For example, the hardening of bituminous materials over time, and the contraction of bitumen could affect the propensity of bitumen pavements to cracking.
	Material type	The causes of cracking typically differ depending on material type with concrete and asphalt materials susceptible to different modes of cracking.
	Total trafficking	It is anticipated that the combined effects of age and trafficking (total trafficking) could affect the propensity of pavements to cracking.
Texture depth	Age	The combination of the age of materials, and the amount of trafficking received could affect texture depth in the following ways. Asphalt materials may become more brittle over time leading to a higher propensity for chip loss. Concrete materials may be susceptible to the loss of material with time and trafficking.
	Total trafficking	
	Material type	Because of their construction different road materials have different nominal texture depths.
Skid resistance	Age Trafficking rate	The combination of age and trafficking rate work together to affect the 'steady state' skid resistance of surfacings.
	Material type	As with texture depth different of road materials have different nominal skid resistance levels.

In cases where a difference in the condition parameters was observed, and a difference in the distribution of additional explanatory variables was observed, histograms of the condition data were plotted, but separated into the categories used to plot the additional explanatory variables. It should be noted that histograms (and Cohen's d-tests (see next section)) were only produced in cases where at least 100 km of data were available.

F.2 Stage2: Perform a Cohen's d-test on the split data and produce bubble plots.

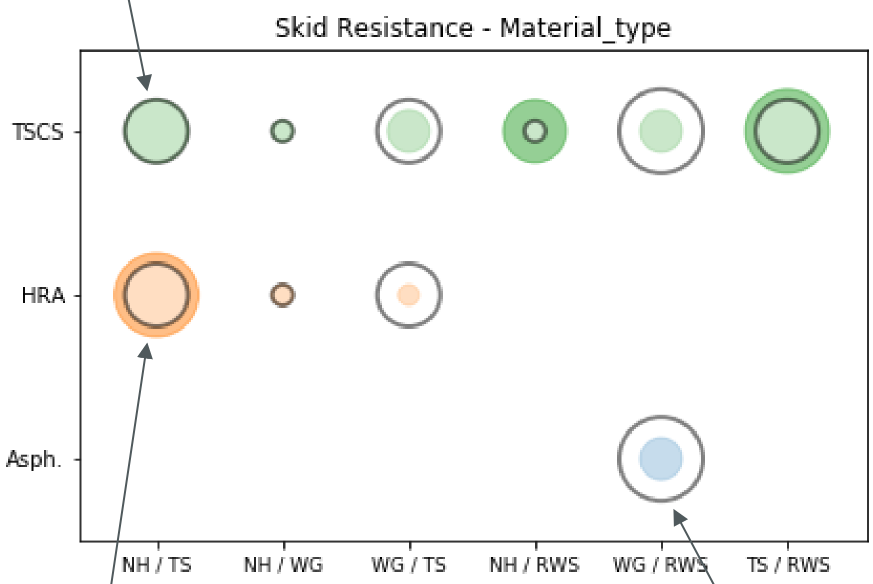
The results of the deeper dive are summarised as a series of 'bubble plots'. These plots present the results of the Cohen's d-tests as a series of different sized circles, the area of which represent the level of agreement between two datasets. For all bubble plots the following conventions have been used:

- Coloured series, represent parameter data assessed from the deeper dive and transparent series (the black circles) represent parameter data from the national benchmarking.
- The area of the series markers ("bubbles") represents the results of the Cohen's d-test; a large area indicates a strong relationship, and a small area indicates a weak relationship.

Figure F-6 presents an annotated example using skid resistance parameter data from the deeper dive split by material type.

In this case the coloured series has **the same** area than the transparent series.

Therefore a **similar** relationship was observed between the national benchmarking and deeper dive for the NH and WG networks on TSCS materials.



In this case the coloured series has a **larger** area than the transparent series.

Therefore a **stronger** relationship was observed between the national benchmarking and deeper dive for the NH and TS networks on HRA materials.

In this case the coloured series has a **smaller** area than the transparent series.

Therefore a **weaker** relationship was observed between the national benchmarking and deeper dive for the WG and RWS networks on asphalt materials.

Figure F-6 Interpreting bubble plots

F.3 Stage 3: Assessment of explanatory power

The assessment of explanatory power supports the conclusions of the deeper dive by considering the distributions of condition data, and results of the Cohen's d-tests. This will produce one of three outcomes:

- **Sufficiently explained** – In cases where the distributions are similar across all additional explanatory variables and between all networks then the additional explanatory variables have sufficiently explained the differences in network condition (parameter data) observed in the national benchmarking.
- **Partly explained** - In cases where the distributions are similar across the majority of additional explanatory variable categories and/or between the majority of networks

then the additional explanatory variables have partly explained the differences in network condition observed in the national benchmarking.

- **Not explained** - In cases where the distributions are different across the majority of additional explanatory variable categories and/or between the majority of networks then the additional explanatory variables have not explained the differences in network condition observed in the national benchmarking.

The assessment of explanatory power was carried out as a purely statistical exercise. The outcomes of the deeper dive therefore represent the outcomes of a statistical analysis. Some comment may however be given based on the author’s wider engineering knowledge but it should be noted that such comments did not form part of the assessment of explanatory power.

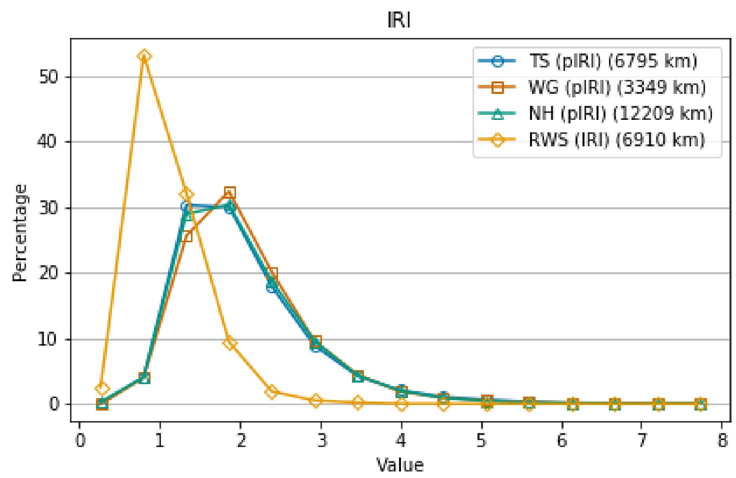
Appendix G Results of the deeper dive

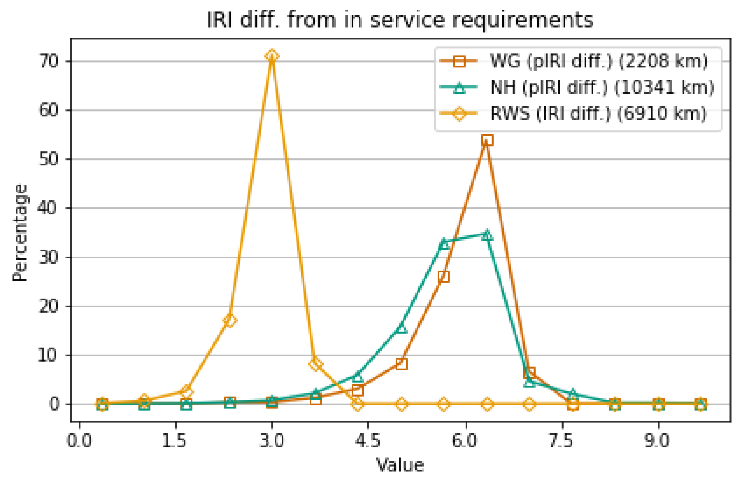
The results of the deeper dive are presented in this section, each sub section begins with a repeat of the results from the national benchmarking, through the presentation of the condition histogram and the histogram of differences from the in-service requirements, for the condition parameter being assessed.

The breakdown of these data by additional explanatory variables is then presented by showing the histograms of parameter data split by the additional explanatory variables, and the bubble plot results of the Cohen's d-test.

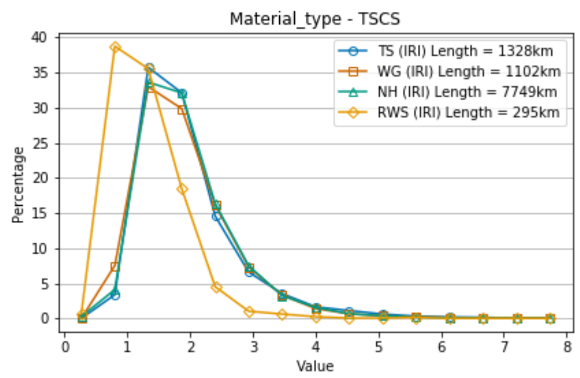
It should be noted that where material type has been considered in the deeper dive, distributions for porous asphalts on the RWS network have been included. These distributions have been included as they represent the overwhelming proportion of the RWS network for which there is an insufficient amount of comparator data from the UK networks. These distributions are for reference only and do not necessarily form part of the analysis

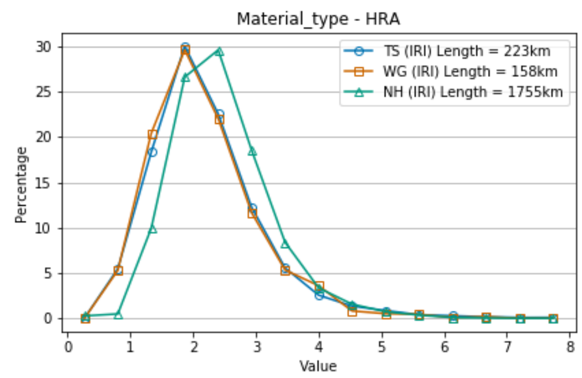
G.1 IRI

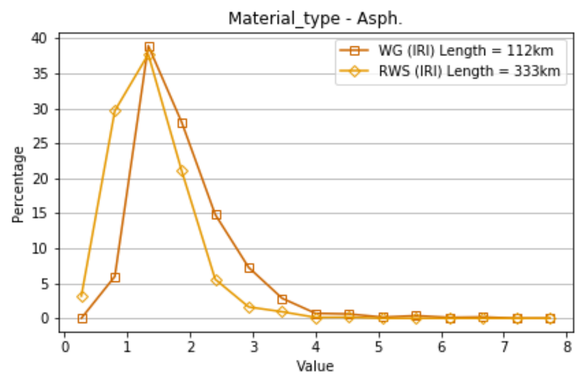


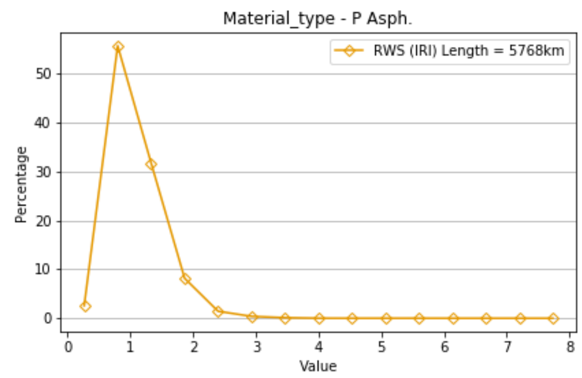


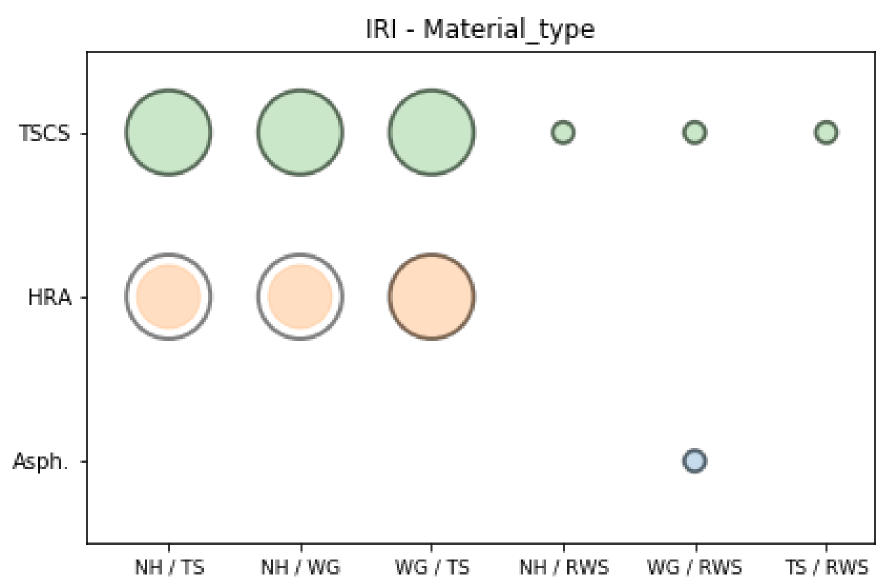
G.1.1 IRI - Material type











Observations: The results from TSs mirror the results of the national benchmarking.

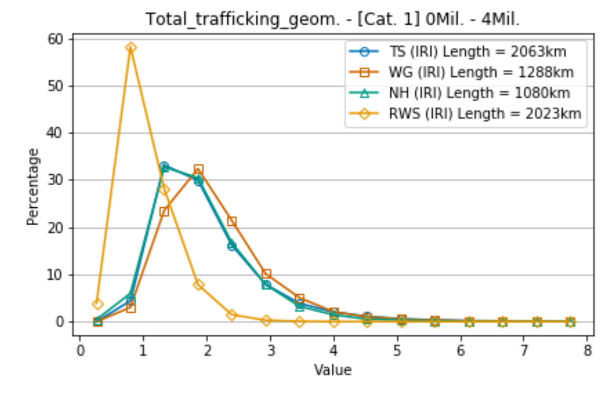
The results from HRAs demonstrate a larger difference between the condition of the UK NRAs than was observed during the national benchmarking.

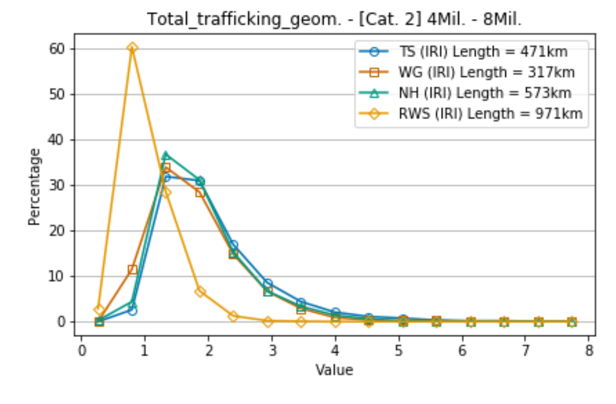
Explanatory power: Not explained.

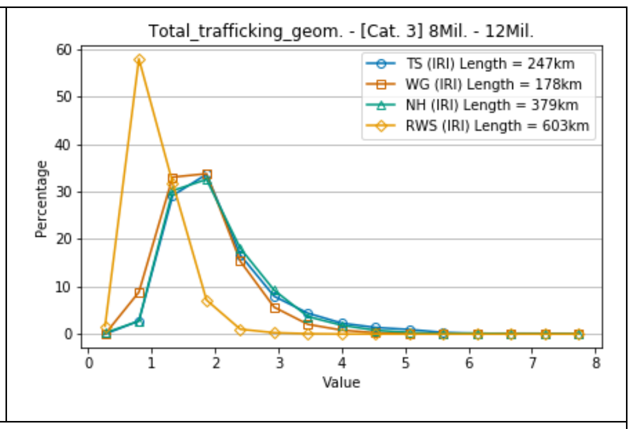
Recommendation: It was noted during the selection of additional explanatory variables that an assessment of material type below the surface layer could offer additional insight into the effect of materials on IRI. For example, it is anticipated that asphalt surface materials laid on a concrete base should be less susceptible to changes in longitudinal profile than asphalt surface materials laid on an asphalt base.

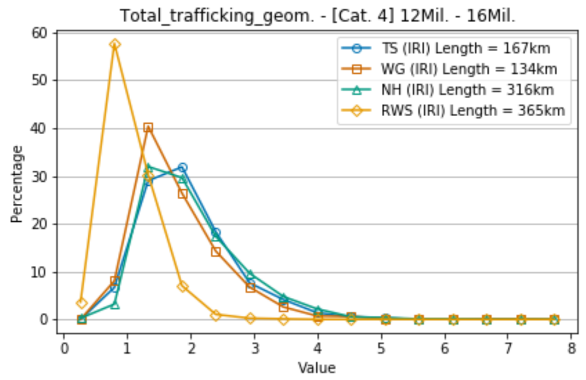
It is therefore recommended that a wider analysis be conducted assessing data from all construction layers.

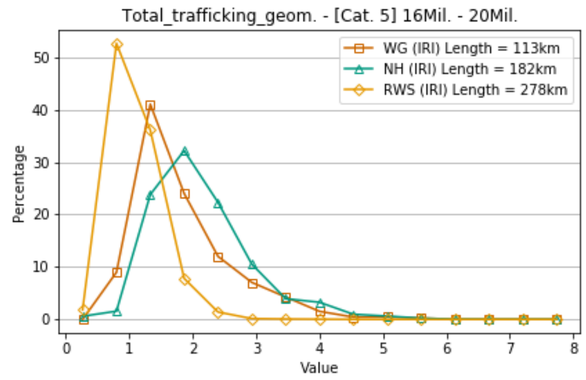
G.1.2 IRI – Total trafficking

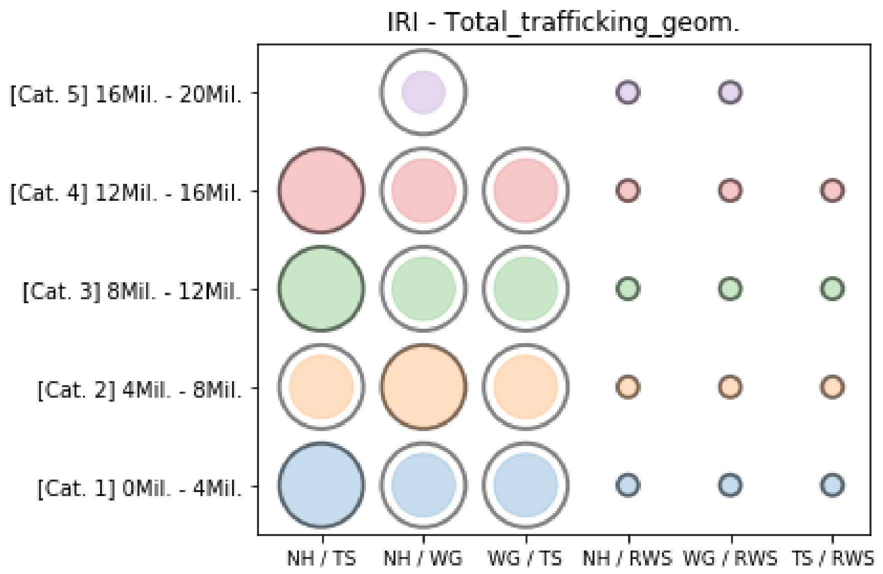












Observations: The results from all categories largely mirror those from the national benchmarking but with a lower amount of agreement between the UK NRAs.

The data presented here are clear in that assessing IRI based on the total amount of trafficking received does not provide an explanation as to the disagreement between networks observed in the national benchmarking.

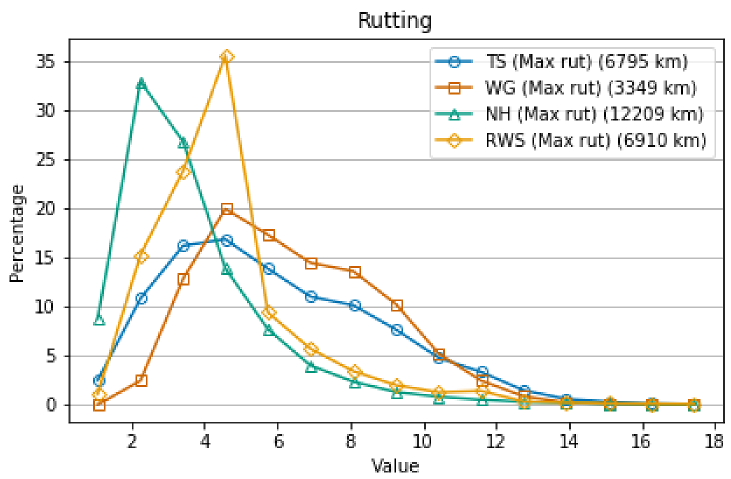
Explanatory power: Not explained.

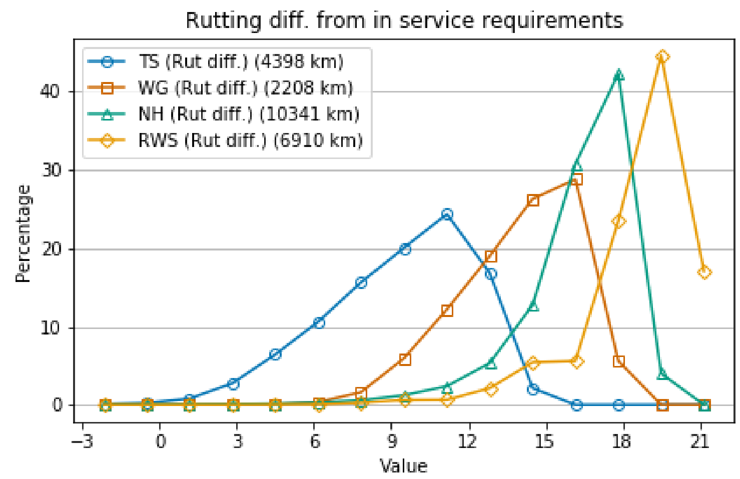
Recommendation: None.

G.1.3 IRI – Overall recommendations

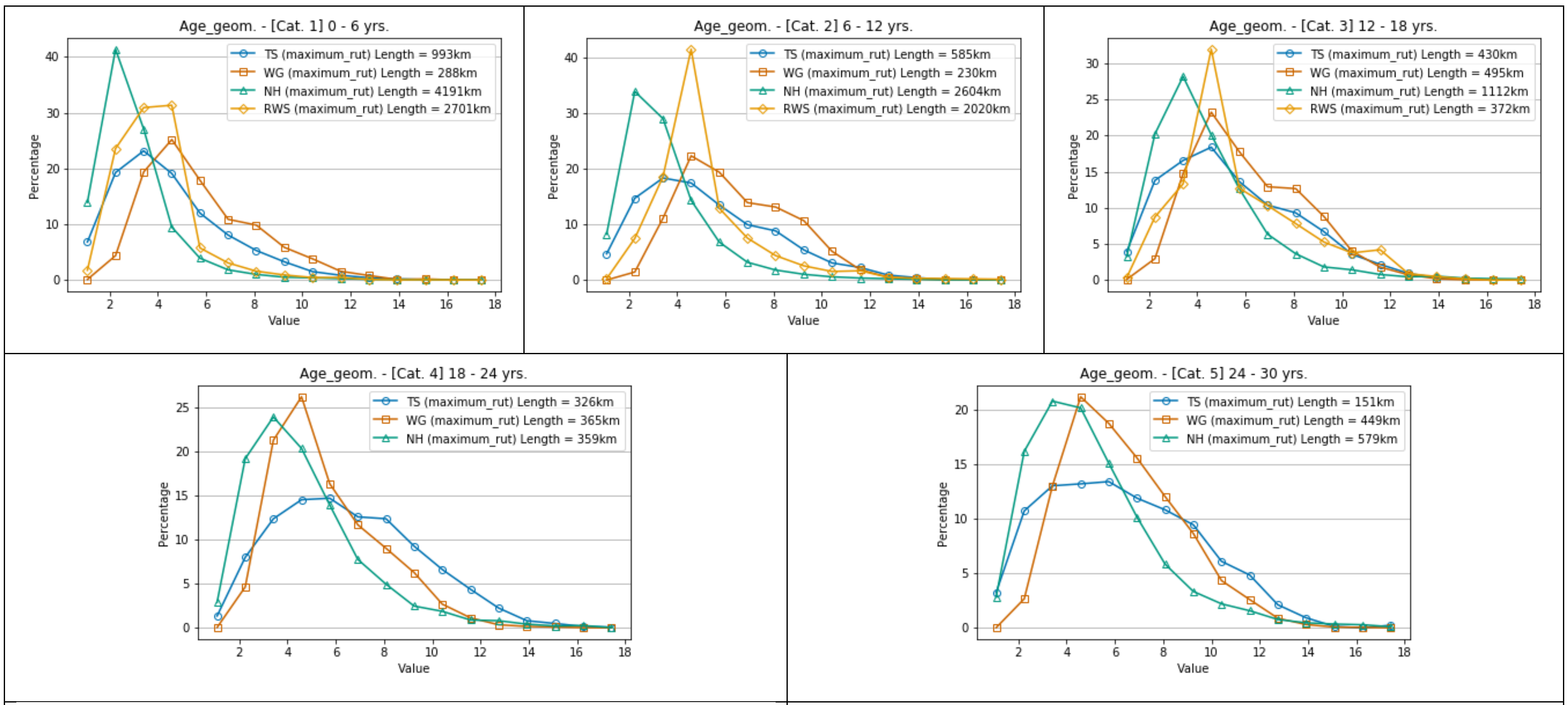
Based on the data presented here it is recommended that future analyses include an assessment of material types at all layers of construction.

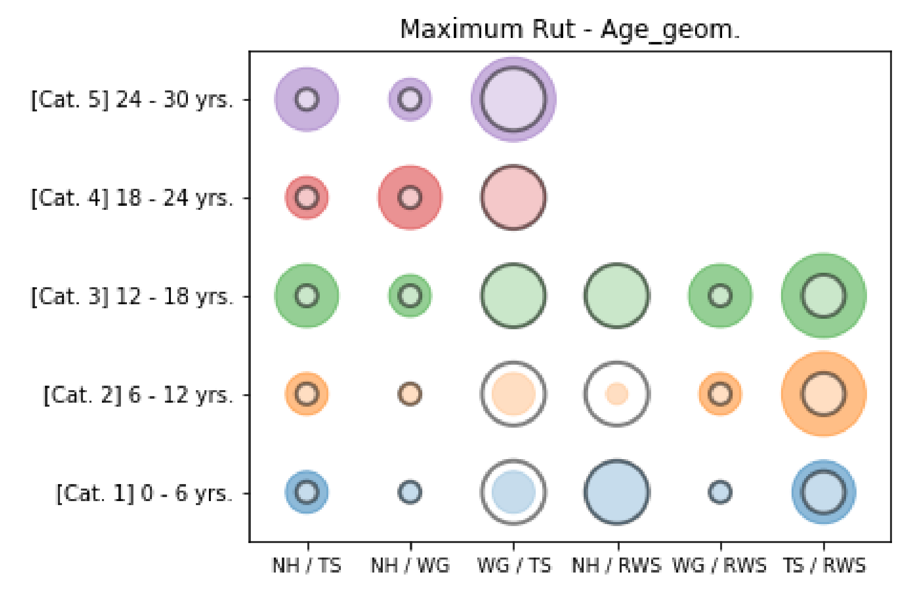
G.2 Rutting





G.2.1 Rutting - Age





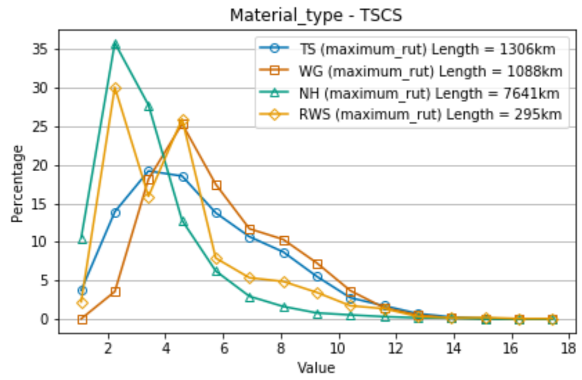
Observations: For age categories 1 and 2 the relationships shown in the national benchmarking data are somewhat reduced, this is particularly apparent for the TS / RWS comparison which demonstrated a small difference.

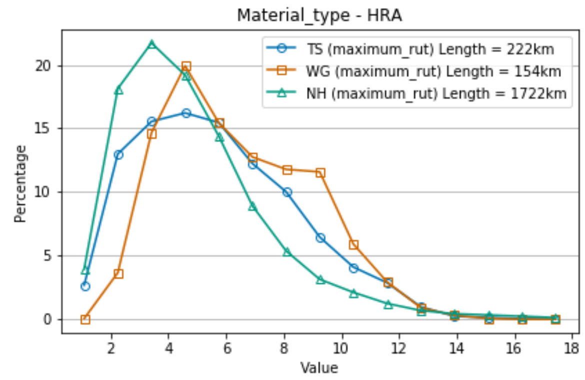
For the remaining categories, a much closer behaviour between networks is observed. It is clear therefore that an assessment of age can partly explain the differences between the differences in rutting between networks observed in the national benchmarking exercise.

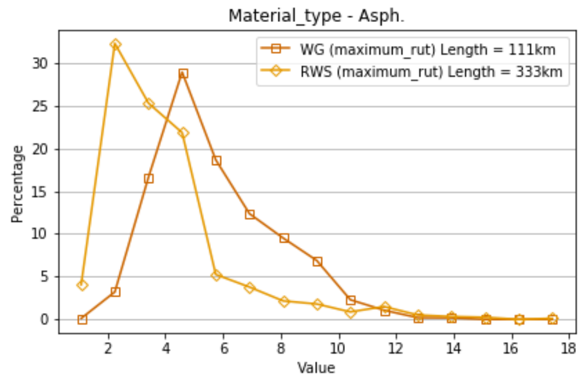
Explanatory power: Partly explains.

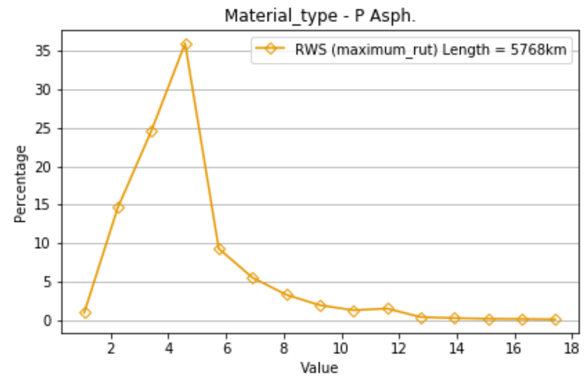
Recommendation: None

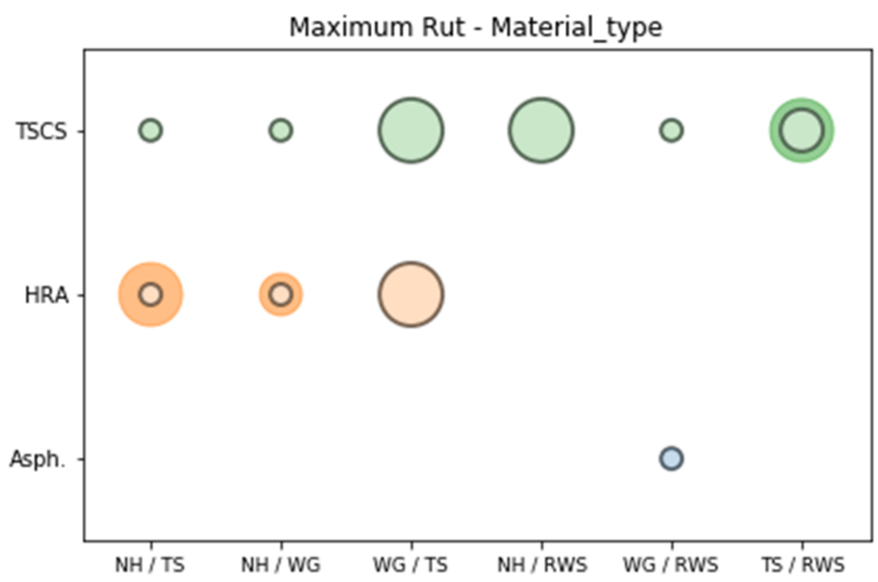
G.2.2 Rutting – Material type











Observations: For TSCSs the behaviour observed in the national benchmarking data was largely replicated. The behaviour of the RWS network however was more similar to the TS network, leading to a reduction in disagreement between these networks.

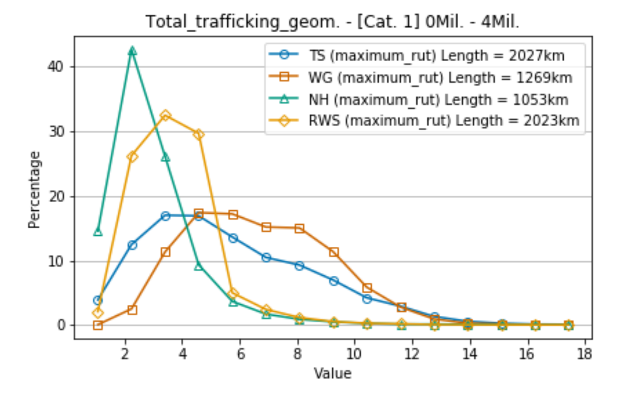
For HRAs the differences between the UK networks were smaller than observed during the national benchmarking exercise. Small differences between the TS and NH/WG networks were observed, and a medium difference between the NH and WG networks was observed.

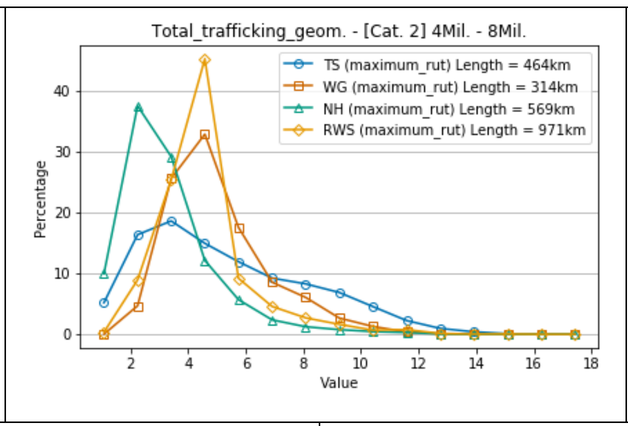
Explanatory power: Partly explains.

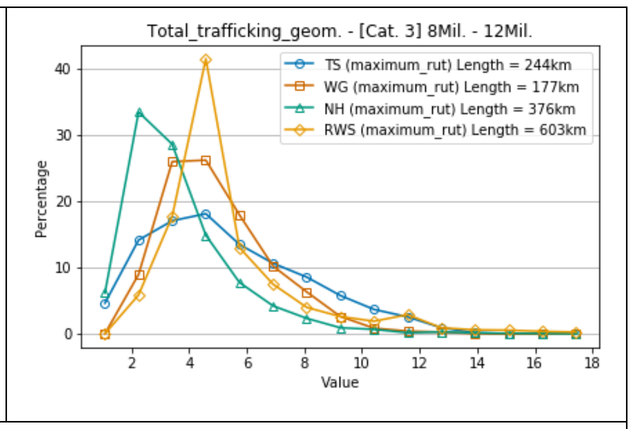
Recommendation: Material type appears to partly explain the differences in rutting shown in the national benchmarking. As with the assessment of IRI it is anticipated that materials at all construction levels could influence the prevalence of rutting.

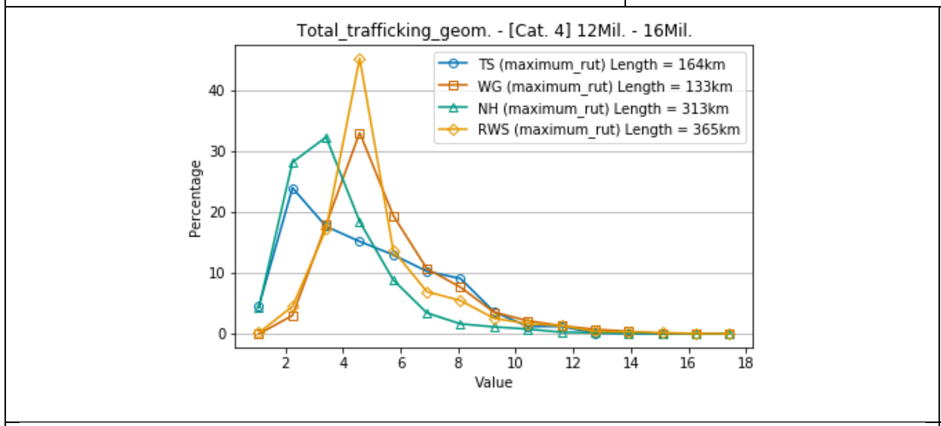
It is therefore recommended that future analyses include an assessment of material type at all construction layers.

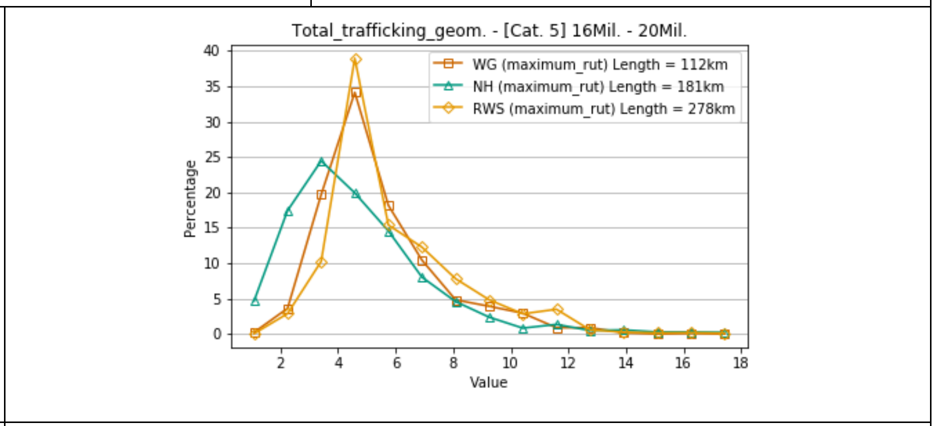
G.2.3 Rutting – Total trafficking

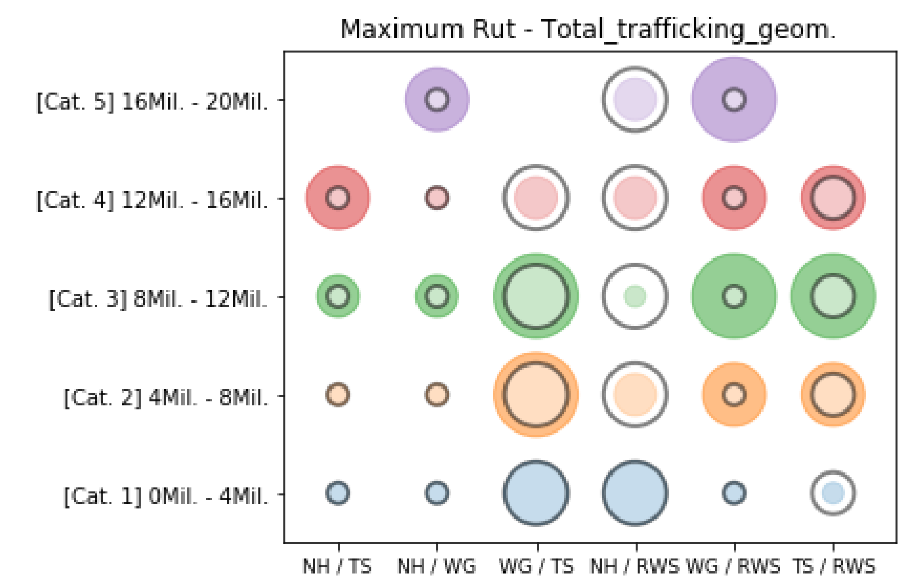












Observations: In comparing the NH network with the other NRAs, it can be seen from the results of the Cohen's d-test that segregating the data by total trafficking offers little explanation of the differences observed in the national benchmarking.

For the RWS network, the relationships with the WG and TS networks (as determined through the Cohen's d-test) improve markedly after 4 million HGV passes. The histograms indicate that this improvement is driven by two factors:

1. A change in the shape of the WG distribution (to conform more to the shape of the RWS distribution); and
2. The shifting of the RWS peak to the right of the distribution with increasing total trafficking.

The explanatory power of the total trafficking appears, on the whole, lower than that for material age. But does offer some valuable insight regarding the condition of the RWS network.

Explanatory power: Partly explains.

Recommendation:

Given the relationships observed in the deeper dive between rutting and, age and material type it is recommended that future analyses be carried out by splitting material type by age.

G.2.4 Rutting – Overall recommendations

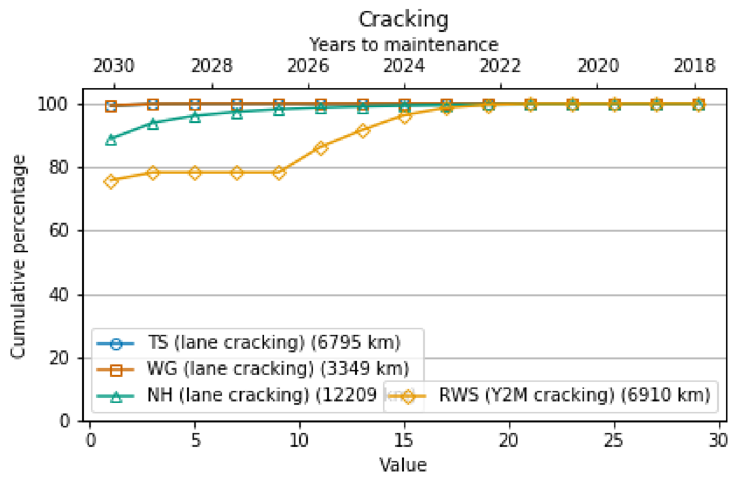
Based on the data presented here it is recommended that future analyses include an assessment of material types at all layers of construction.

An additional factor that was not available for assessment during this work is that of pavement temperature. It is anticipated that for asphalt materials, exposure to high temperatures could make the bitumen more malleable than materials in colder climes. A future analysis may therefore benefit from an assessment of environmental effects.

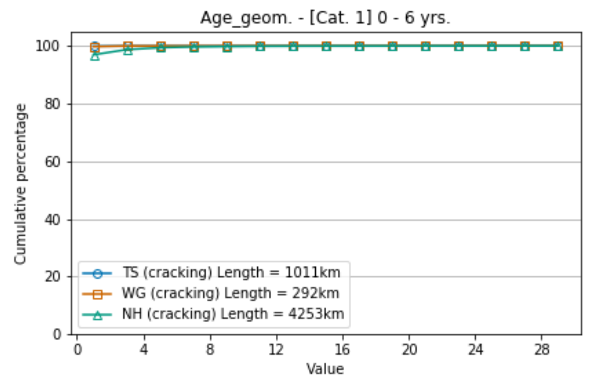
Future analyses may also gain insight from a more granular assessment of material type (for asphalt materials), for example:

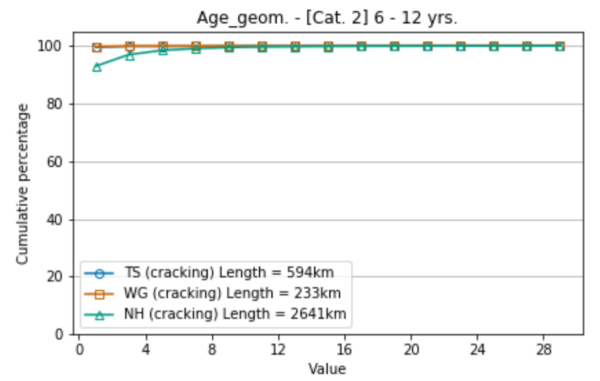
- The grading of the aggregate,
- The type and properties of the bitumen used,
- The use of bitumen additives (e.g. polymer modification),
- The characteristics of the materials / environment during laying.

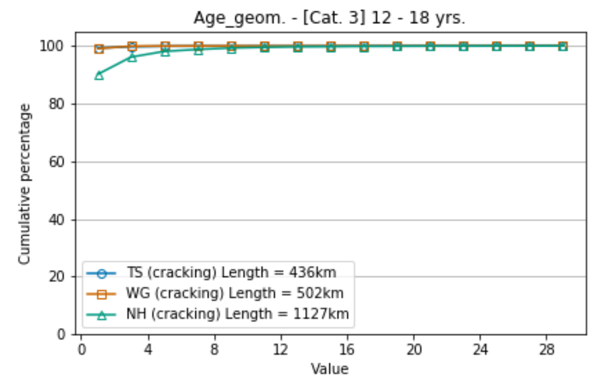
G.3 Cracking

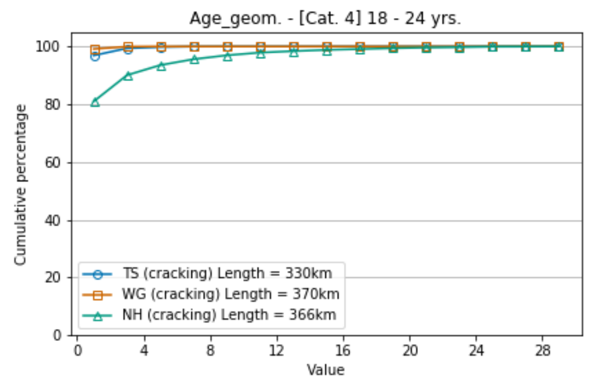


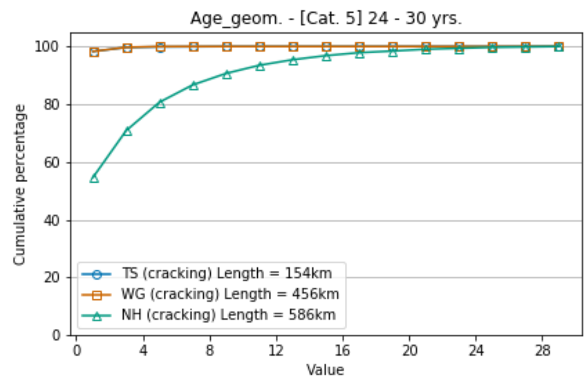
G.3.1 *Cracking - Age*

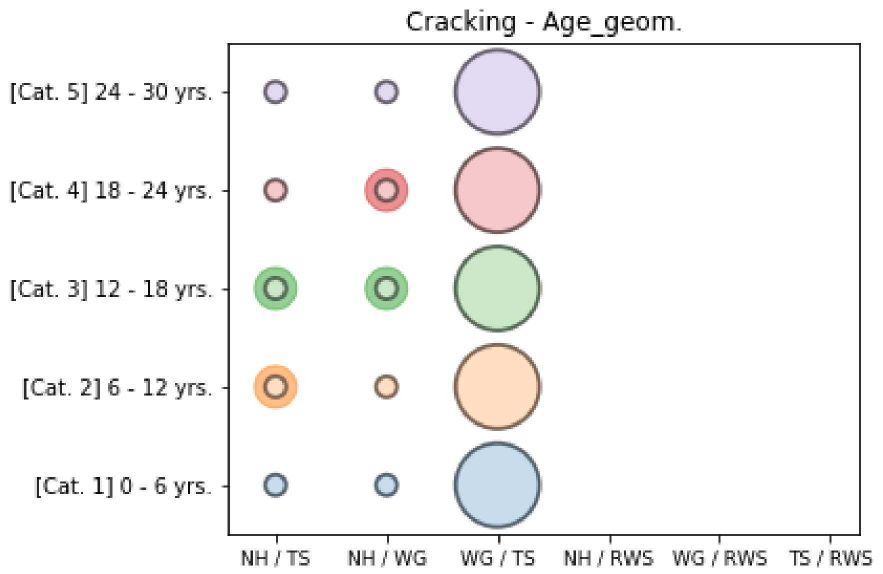












Observations: For all categories, the relationship between the WG and TS NRAs are similar with all categories resulting in a negligible disagreement between these NRAs.

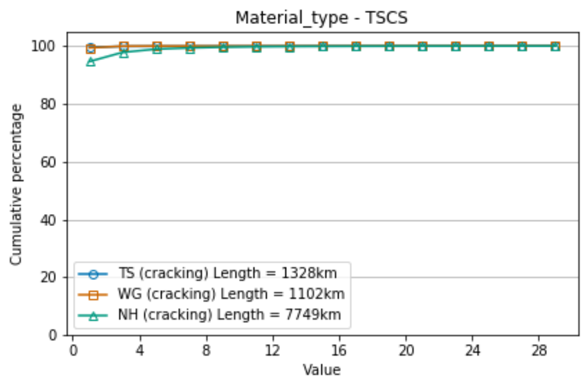
An interesting behaviour is observed in the NH data which shows that cracking increases with age. This is observed in the percentage of lower cracking values occurring on the NH network. In age category 1 lower cracking values account for approximately 95% of the data, whereas in age category 5 this percentage decreases to approximately 55%.

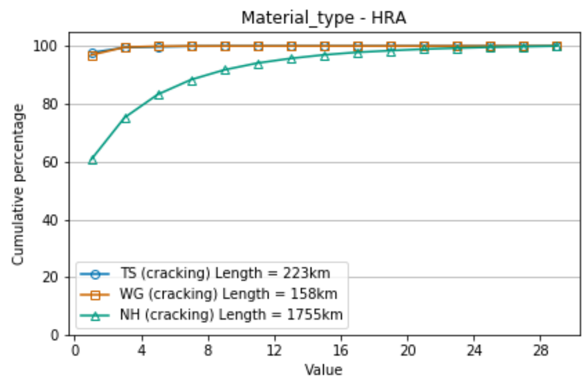
The data presented here suggest material age does not provide an explanation for the observed differences in cracking between the networks.

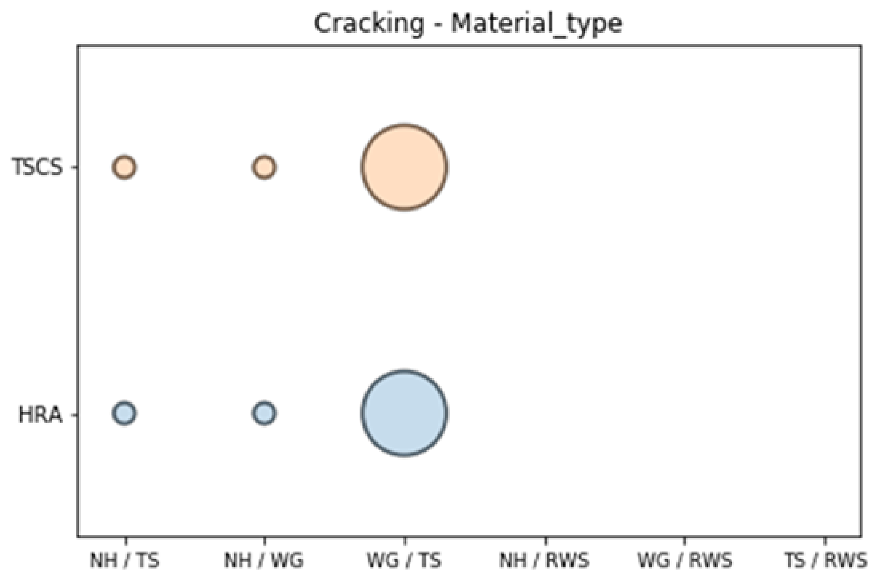
Explanatory power: Not explained.

Recommendation: None.

G.3.2 Cracking – Material type







Observations: For both material types the same amount of disagreement between the NRAs is observed.

Comparing the CFDs for TSCSs with HRAs it appears to be the case that greater amounts of cracking are observed on HRAs than TSs. It may be the case that this observation is inter-related with age as HRAs (at least on the NH network) are seldom used in newer works.

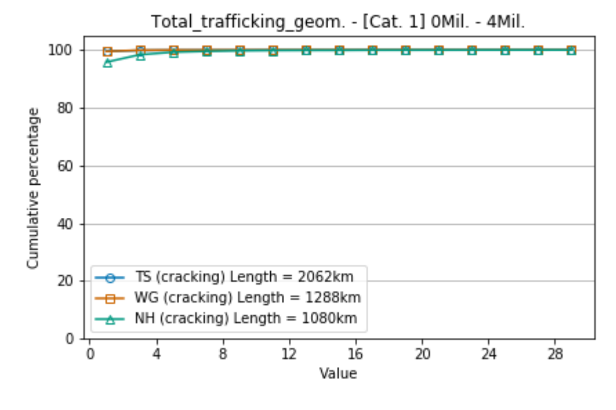
It is interesting to note that the overall cracking of TSCS materials largely align with the overall cracking of age categories 1 and 2, whereas HRAs more closely align with age category 5.

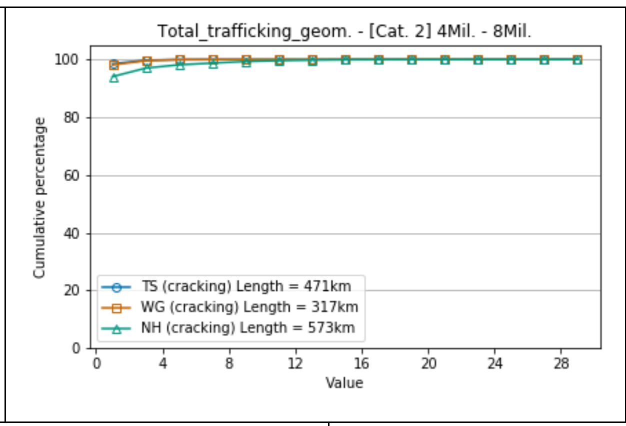
The data presented here suggest material type does not provide an explanation for the observed differences in cracking between the networks.

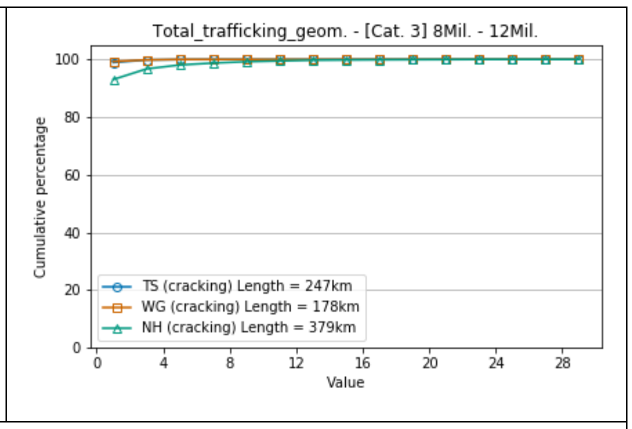
Explanatory power: Not explained.

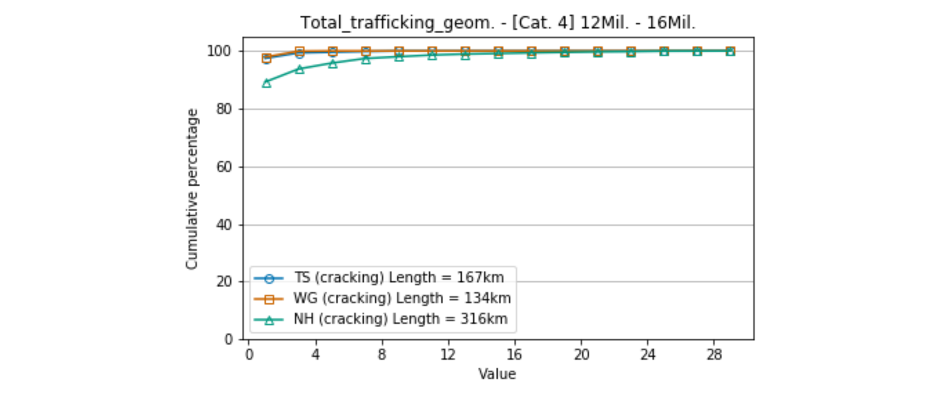
Recommendation: Further insight may be gained by further splitting material type by age and assessing the relationships between material type and material age.

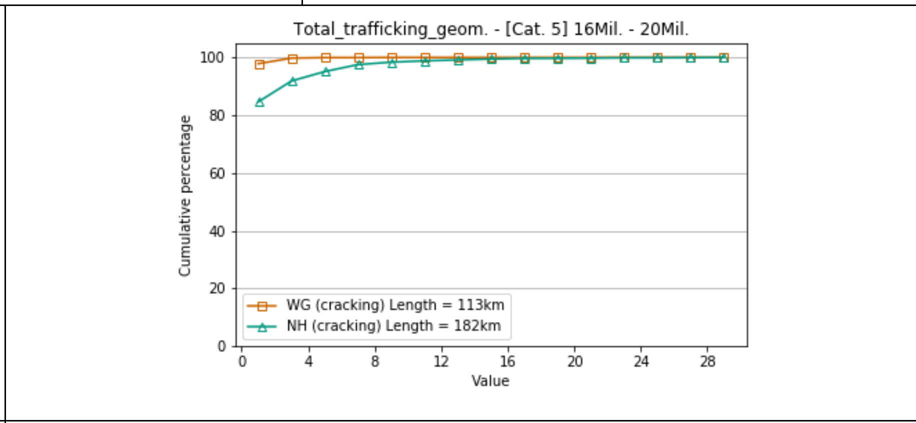
G.3.3 Cracking – Total trafficking

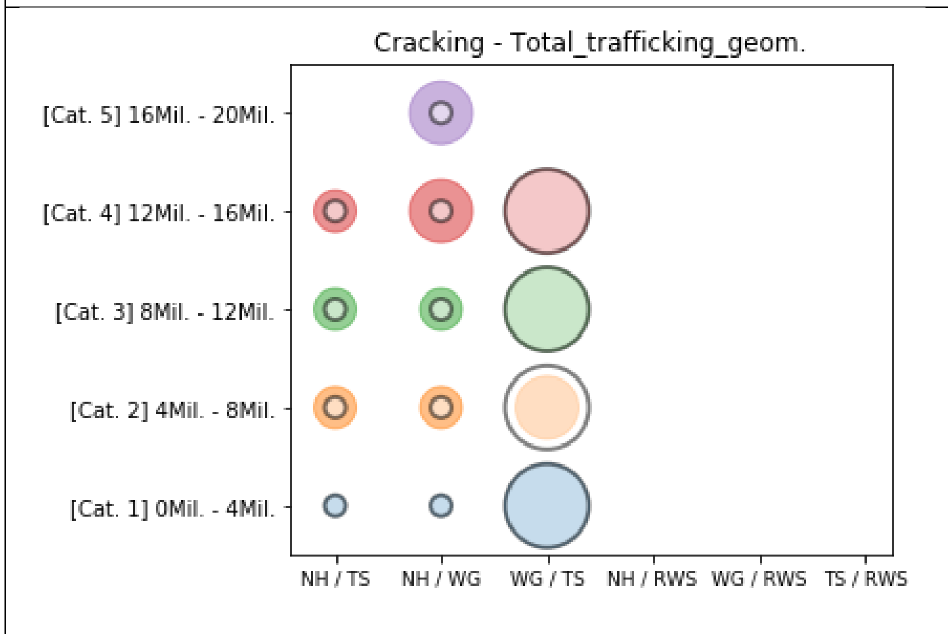












Observations: When comparing the NH network to the other NRAs an interesting behaviour is observed. Within an increase in total trafficking, the amount of agreement between the networks seem to improve.

This is particularly evident when comparting the NH network to the WG network where a small amount of disagreement was observed in categories 4 and 5.

Explanatory power: Partly explains.

Recommendation:

It has been shown that there appears to be a correlation between material age and cracking for the NH network. Total trafficking necessarily includes material age in its derivation. Further insight could therefore be gained by understanding the effect of trafficking rate on cracking prevalence.

G.3.4 Cracking – Overall recommendations

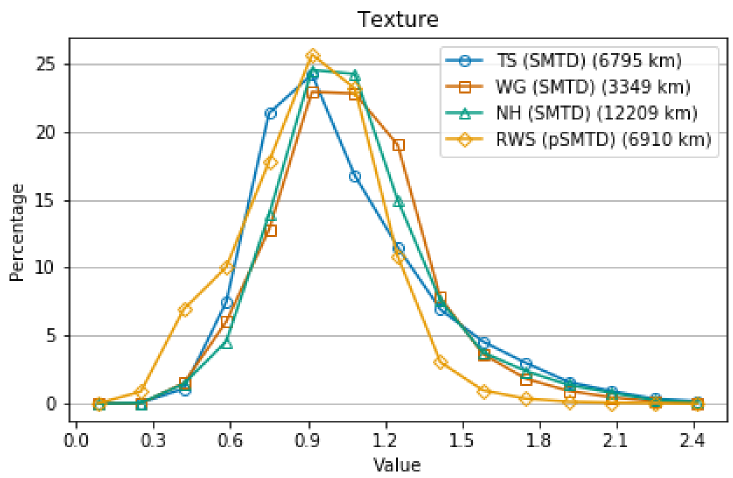
The following recommendations are made regarding the future assessment of cracking:

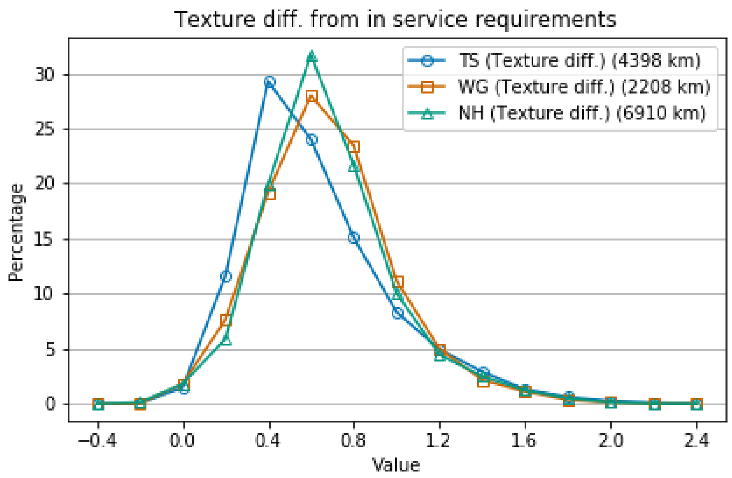
- Whilst none of the parameters assessed here could fully explain the differences in network condition observed during the national benchmarking, it is recommended that the inter-dependency of these parameters be assessed through more sophisticated statistical means (Machine Learning or AI).
- The effect of environmental features on the prevalence of cracking be assessed. For example, it is anticipated that exposure to UV light can have a 'stiffening' effect on bituminous materials.
- The relationship between cracking and trafficking rate should be assessed for materials of similar types and ages.
- NH uses TRACS to characterise cracking whereas the WG and TS use SCANNER. Whilst both methodologies use similar measurement technologies, the algorithms used to process the data differ fairly substantially. .

It is hypothesised that the differences in cracking observed in the national benchmarking are related to the methodologies used to characterise cracking. To test this hypothesis it is recommended that future works:

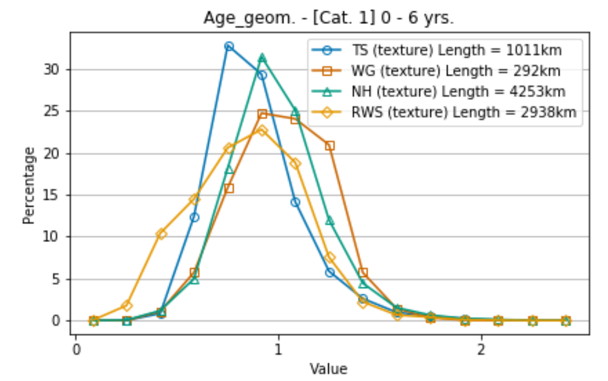
- Investigate the differences in characterisation methodologies in order to produce a correction factor between TRACS and SCANNER, and/or;
- Complete TRACS surveys on the WG and TS networks to allow for a like-for-like comparison of cracking.

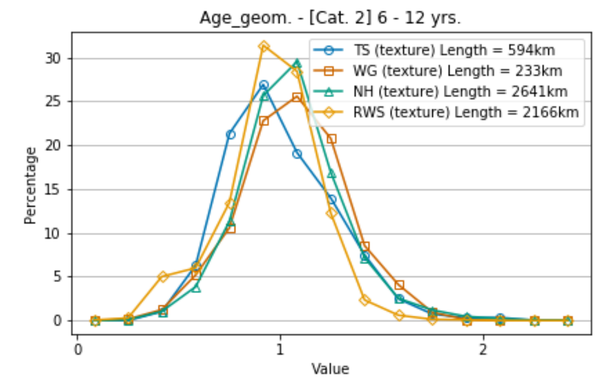
G.4 Texture depth

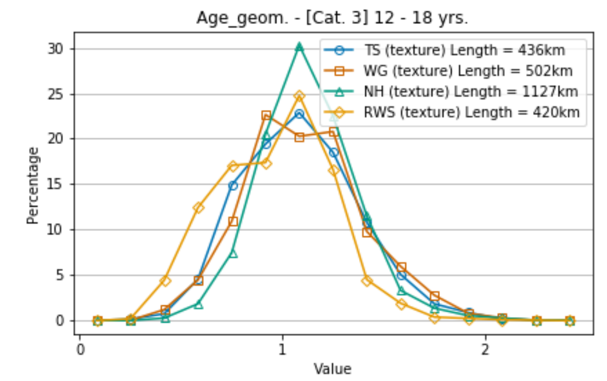


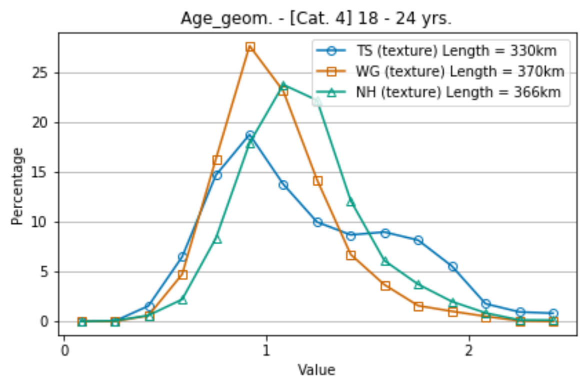


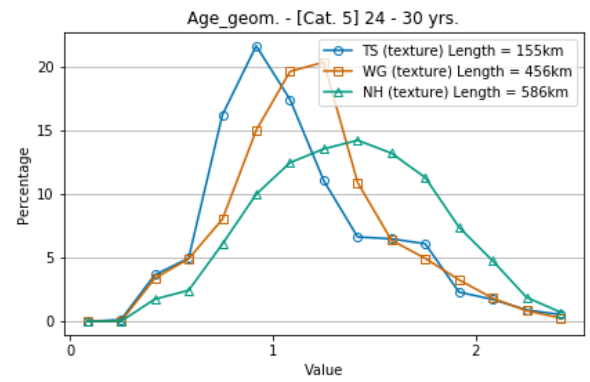
G.4.1 Texture depth - Age

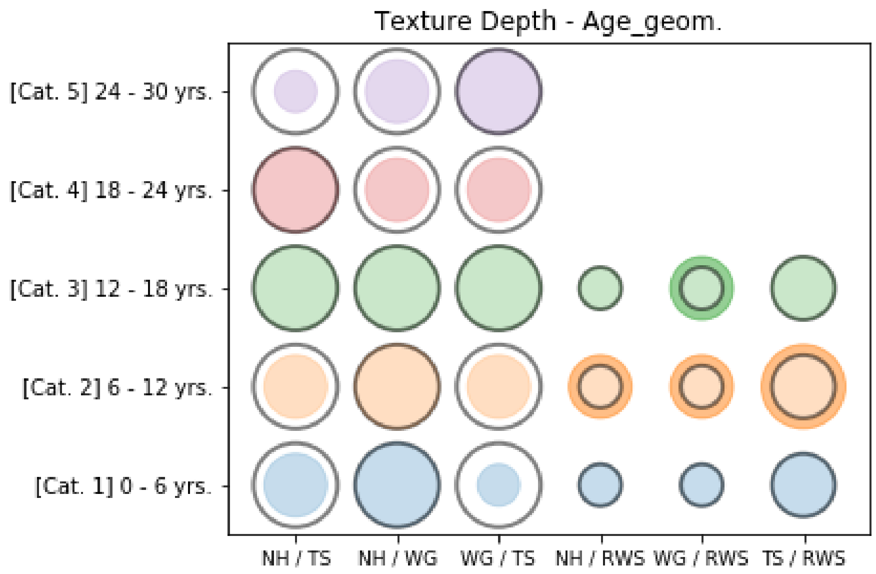












Observations: For all but Categories 2 and 3, the difference in condition between the NRAs diverged on the whole from the national benchmarking.

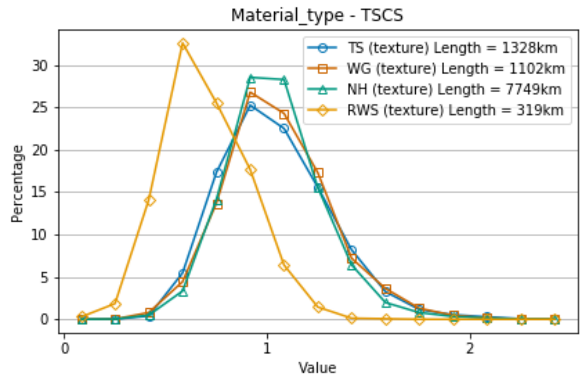
For Categories 2, a slightly better agreement is observed on the whole.

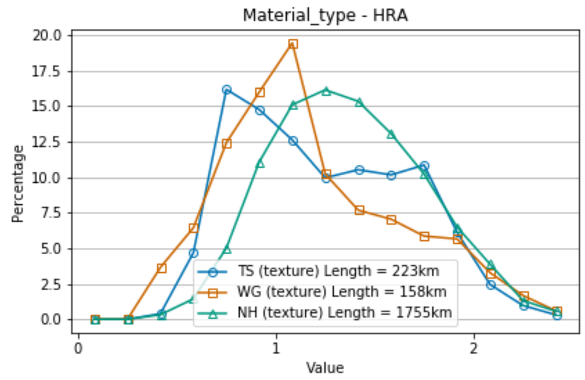
The data presented here demonstrate suggest that material age does not provide a strong explanation for the observed differences in texture depth between the networks.

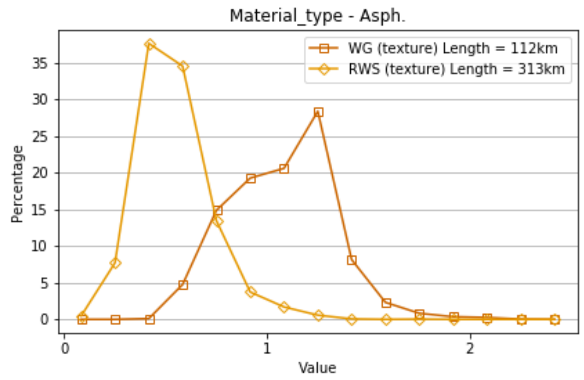
Explanatory power: Not explained.

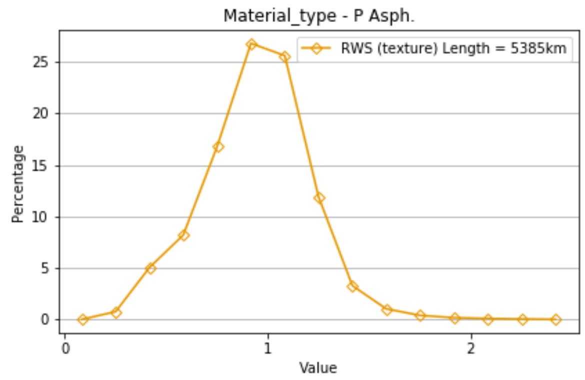
Recommendation: None.

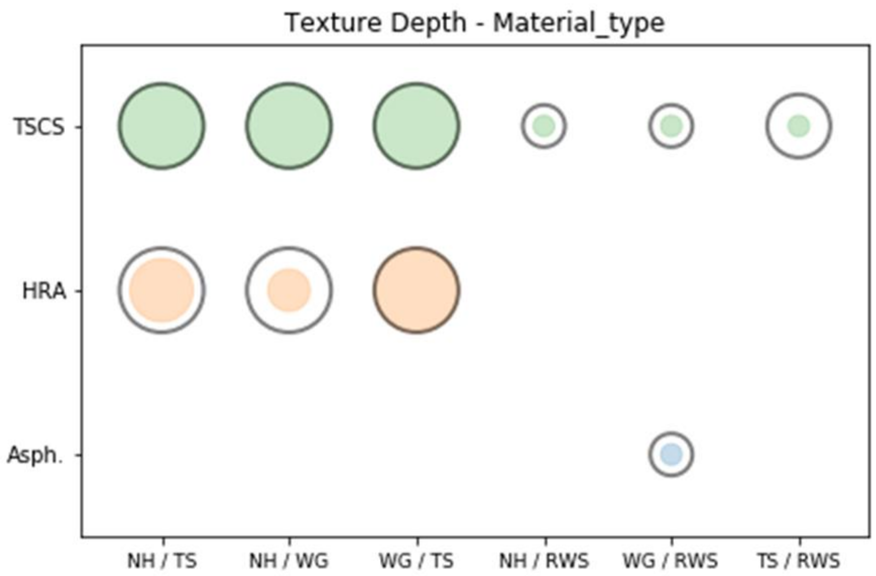
G.4.2 Texture depth – Material type











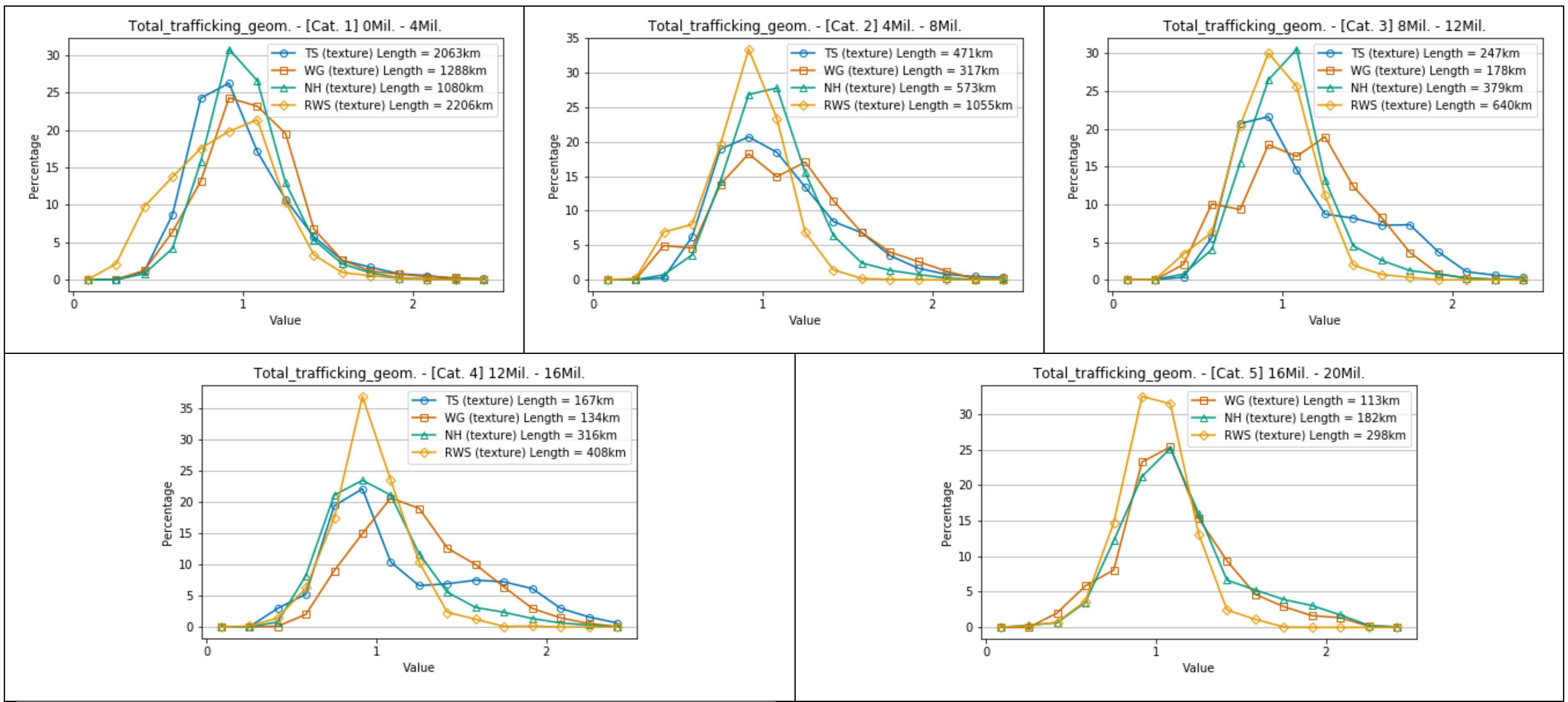
Observations: Whilst some networks demonstrated the same amount of agreement with the national benchmarking exercise, on the whole, splitting the analysis by material type has resulted in a poorer agreement between networks.

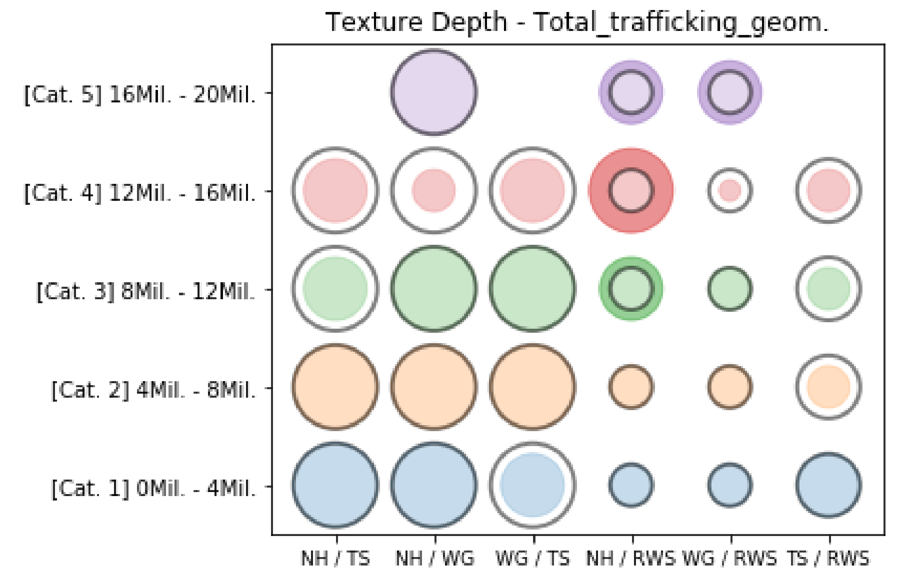
The data presented here demonstrate suggest that material type does not provide a strong explanation for the observed differences in texture depth between the networks.

Explanatory power: Not explained.

Recommendation: None.

G.4.3 Texture depth – Total trafficking





Observations: Whilst some networks demonstrated a greater amount of agreement with the national benchmarking, on the whole, splitting the analysis by total trafficking has resulted in a similar agreement between networks.

The data presented here demonstrate suggest that total trafficking does not provide a strong explanation for the observed differences in texture depth between the networks.

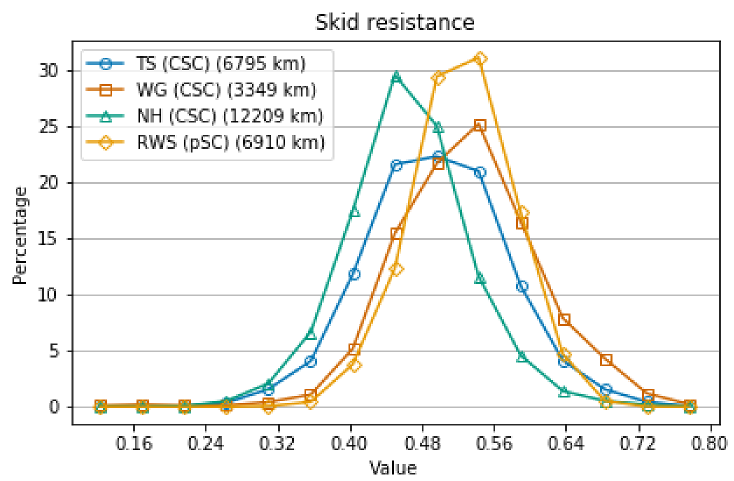
Explanatory power: Not explained.

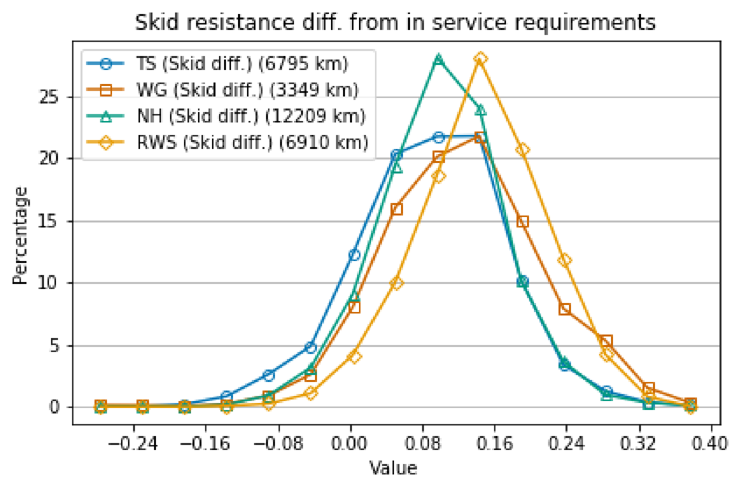
Recommendation: None.

G.4.4 Texture depth – Overall recommendations

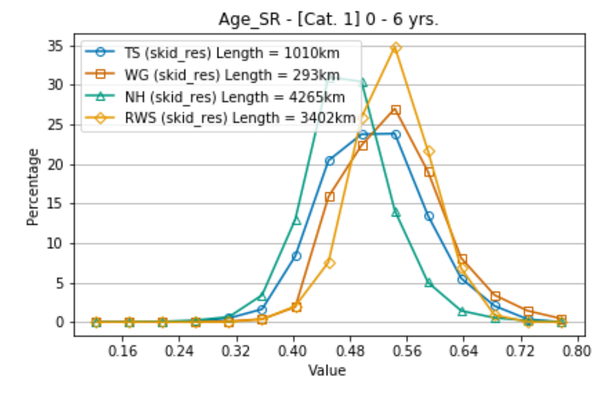
No specific recommendations regarding texture depth were made as part of the deeper dive, however it is recommended that a more granular assessment of material type on texture depth be carried out. It is generally accepted that the specific formulation of road materials can have a substantial effect on their texture depth. For example, TS materials may have nominal aggregate sizes ranging between 6mm and 20mm.

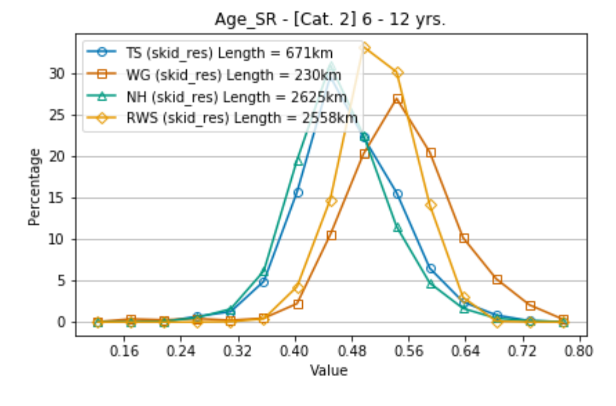
G.5 Skid Resistance

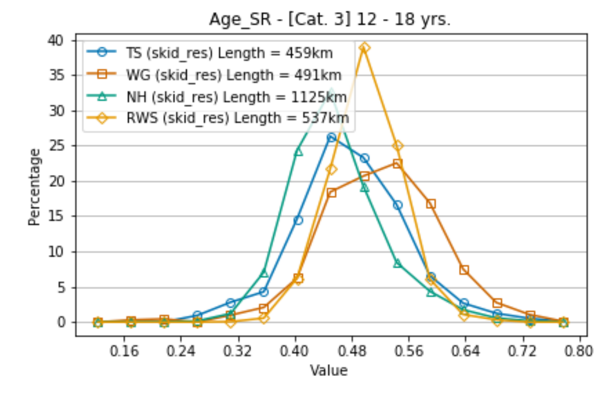


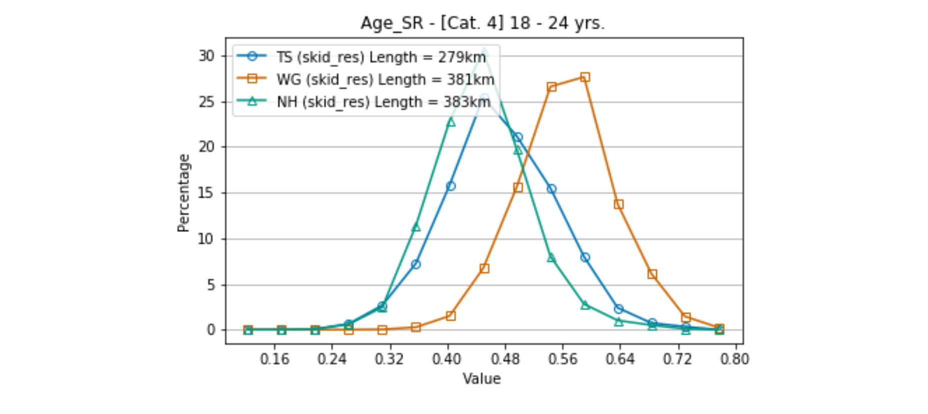


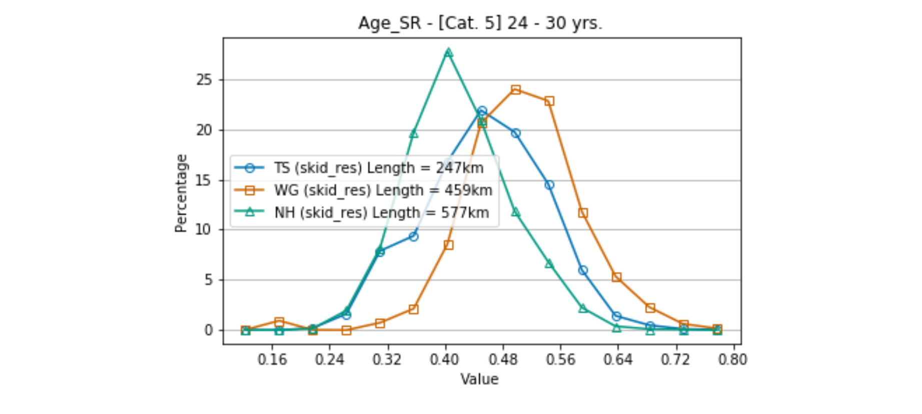
G.5.1 Skid resistance – Age

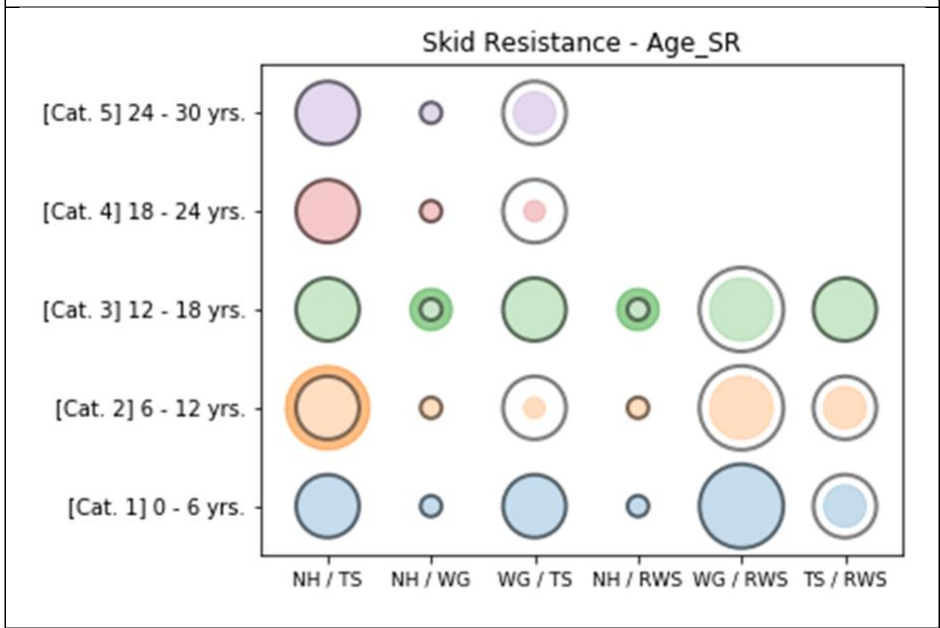












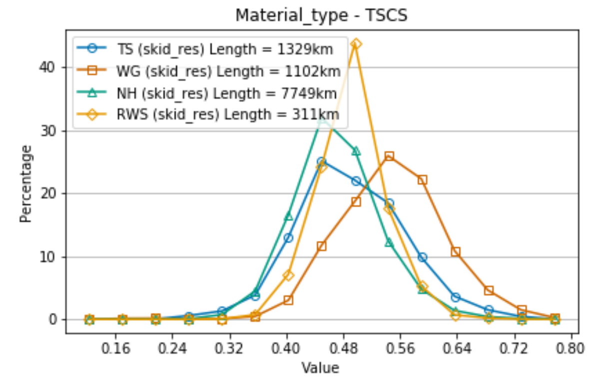
Observations: For all categories the level of agreement between the networks was, on the whole, similar to that observed in the national benchmarking. Whilst some combinations of ages and networks provided better agreement than that observed in the national benchmarking, this was not consistent enough to provide any explanatory power.

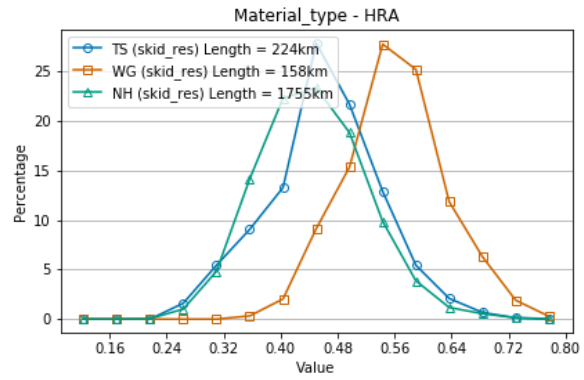
This finding is particularly interesting given that the RWS network demonstrated a substantially different distribution of material ages in comparison to the UK networks. It is also noted that the RWS network is primarily comprised of porous asphalt materials and the distribution of material ages for that material type may differ substantially in comparison to other material types.

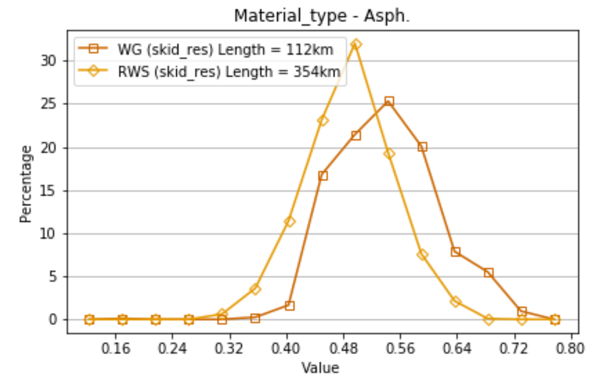
Explanatory power: Not explained.

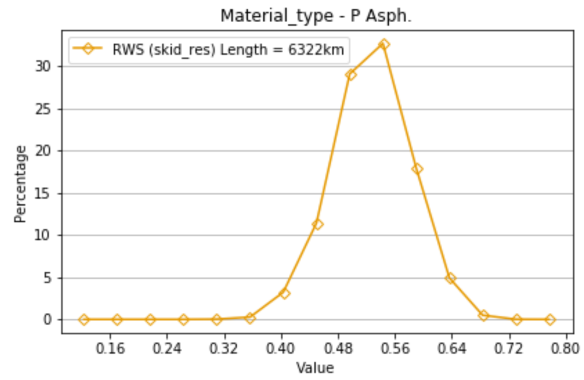
Recommendation: None.

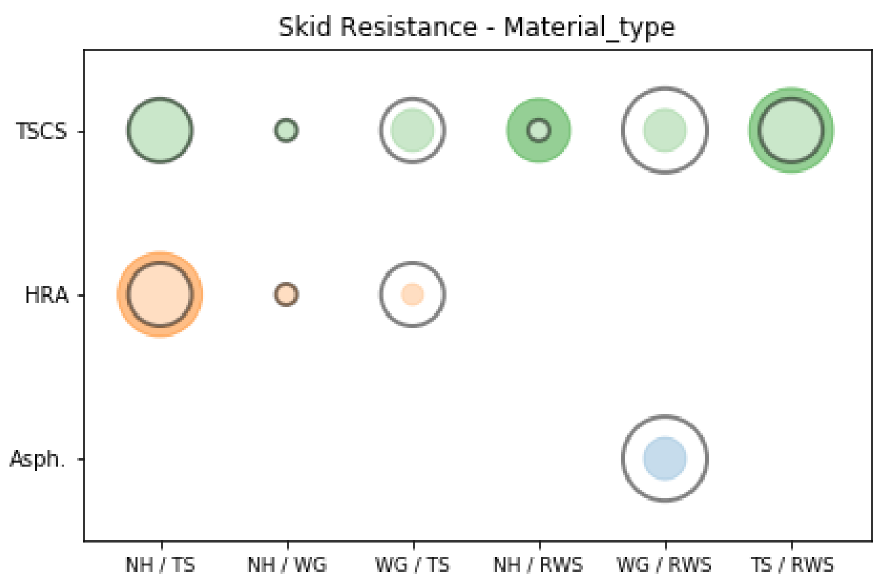
G.5.2 *Skid resistance – Material type*











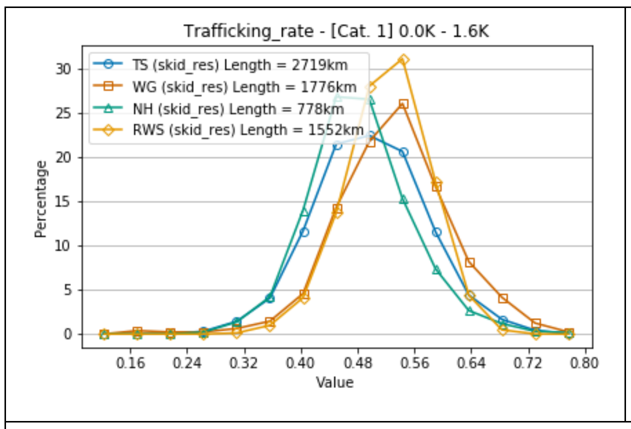
Observations: When splitting the national benchmarking data by material type, the level of agreement between the networks was, on the whole, similar to that observed in the national benchmarking. Whilst some materials and networks provided better agreement than that observed in the national benchmarking, this was not consistent enough to provide any explanatory power.

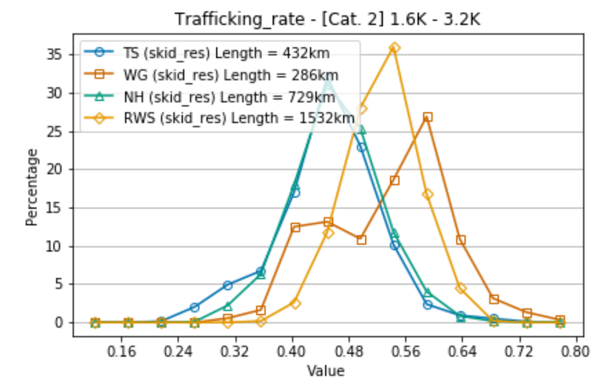
Explanatory power: Not explained.

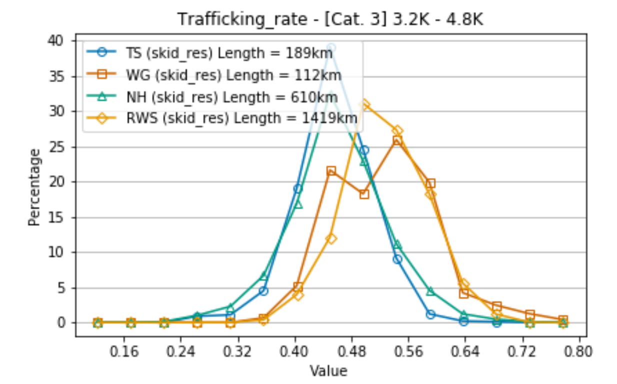
Recommendation: The data presented here show that the material type with the most explanatory power is thin surfacings. Continuing the discussion of material ages from above, previous research ((Roe & Lagarde-Forest, 2005), (Greene & Crinson, 2008), and (Greene, Sanders, & Roe, 2010)) has demonstrated that TSs have a early life period (between 0 and 5 years) where substantial changes in skid resistance can occur.

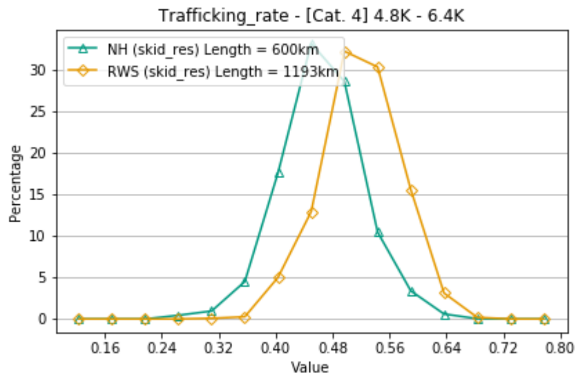
It is therefore recommended that future analyses assess the inter-dependency between material type and age to determine the explanatory power of the combined effects of material type and age.

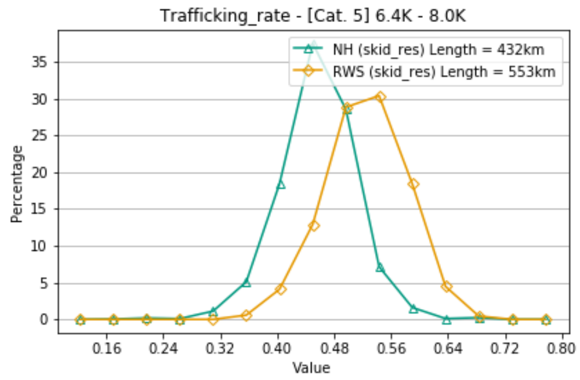
G.5.3 *Skid resistance – Trafficking rate*

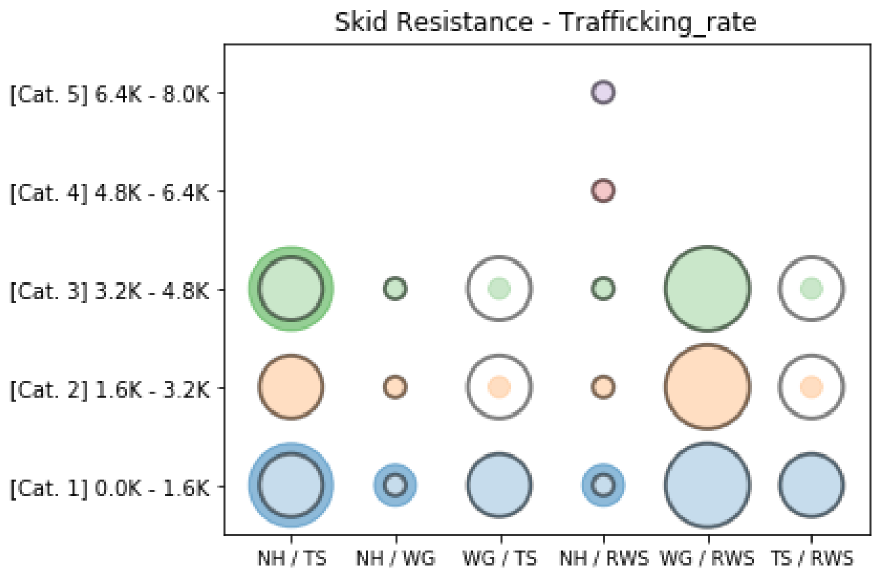












Observations: In splitting the skid resistance data by trafficking rate, the overall agreement between the networks is lower than that observed in the national benchmarking. The key exception to this is that generally better agreements between the networks were observed on roads with the lowest trafficking rates (category 1).

Explanatory power: Partly explains.

Recommendation: The observations made here support the hypothesis that there is an interplay between material type and age as trafficking rate is a factor in this relationship.

G.5.4 *Skid resistance – Overall recommendations*

Based on the data presented here it is recommended that future analyses building on the work of (Roe & Lagarde-Forest, 2005), (Greene & Crinson, 2008), and (Greene, Sanders, & Roe, 2010) include an assessment of the inter-related effects of material type, material age, and trafficking rate.

It is also recommended that future analyses split the data by the in-service requirements of the networks.

Appendix H Deeper dive summary statistics

H.1 IRI

H.1.1 IRI – Material type

Split	Authority	Length (km)	mean	Stdev	Skew	kurtosis
Asph.	WG	112	1.869	0.789	2.415	14.176
	RWS	333	1.345	0.563	1.269	5.936
HRA	NH	1,755	2.448	0.78	0.959	5.192
	WG	158	2.176	0.874	1.462	7.624
	TS	223	2.221	0.932	1.749	9.006
TSCS	TS	1,328	1.961	0.832	2.2	10.728
	WG	1,102	1.912	0.798	2.143	12.993
	NH	7,749	1.931	0.737	1.583	7.641
	RWS	295	1.291	0.546	1.972	10.973

H.1.2 IRI – Total trafficking

Split	Authority	Length (km)	mean	Stdev	Skew	kurtosis
[Cat. 1] 0Mil. - 4Mil.	RWS	2023	1.03	0.398	1.728	9.184
	TS	2063	2.006	0.873	2.09	10.549
	WG	1288	2.14	0.843	1.921	10.457
	NH	1080	1.913	0.742	1.348	6.627
[Cat. 2] 4Mil. - 8Mil.	RWS	971	1.024	0.37	1.644	7.615
	NH	573	1.882	0.695	1.343	5.825
	WG	317	1.818	0.766	2.336	18.851
	TS	471	2.053	0.86	1.911	8.814
[Cat. 3] 8Mil. - 12Mil.	RWS	603	1.045	0.361	1.502	6.899
	NH	379	2.01	0.758	1.55	7.313
	WG	178	1.812	0.724	4.486	65.489
	TS	247	2.076	0.871	1.908	8.415
[Cat. 4] 12Mil. - 16Mil.	TS	167	1.952	0.751	1.496	7.648
	RWS	365	1.031	0.372	1.695	9.329
	NH	316	2.012	0.758	1.174	4.994
	WG	134	1.792	0.693	1.648	8.198
[Cat. 5] 16Mil. - 20Mil.	NH	182	2.136	0.78	1.168	5.328
	WG	113	1.824	0.767	1.524	5.788

	RWS	278	1.085	0.358	1.634	8.281

H.2 Rutting

H.2.1 Rutting – Age

Split	Authority	Length (km)	mean	Stdev	Skew	kurtosis
[Cat. 1] 0 - 6 yrs.	**TS**	993	4.471	2.356	1.039	4.29
	WG	288	5.736	2.294	0.921	3.593
	NH	4191	3.029	1.667	2.536	14.555
	RWS	2701	3.678	1.757	1.796	8.778
[Cat. 2] 6 - 12 yrs.	**RWS**	2020	5	2.313	1.591	7.024
	NH	2604	3.528	1.91	2.095	10.483
	WG	230	6.418	2.25	0.592	3.093
	TS	585	5.293	2.791	0.989	4.585
[Cat. 3] 12 - 18 yrs.	**NH**	1112	4.51	2.524	2.287	11.708
	RWS	372	5.667	2.662	0.814	3.481
	TS	430	5.45	2.727	0.717	3.225
	WG	495	6.133	2.301	0.748	4.065
[Cat. 4] 18 - 24 yrs.	**TS**	326	6.564	2.986	0.559	3.2
	WG	365	5.564	2.2	0.994	4.228
	NH	359	4.71	2.453	1.436	5.84
[Cat. 5] 24 - 30 yrs.	**NH**	579	5.092	2.671	1.442	6.196
	WG	449	6.303	2.335	0.729	3.605
	TS	151	6.299	3.069	0.407	2.576

H.2.2 Rutting – Material type

Split	Authority	Length (km)	mean	Stdev	Skew	kurtosis
Asph.	**WG**	111	5.692	2.067	0.782	3.225
	RWS	333	3.769	2.485	2.355	11.483
HRA	**NH**	1722	4.881	2.642	1.457	6.257
	WG	154	6.403	2.503	0.509	2.72
	TS	222	5.659	2.73	0.567	2.958
TSCS	**TS**	1306	5.263	2.623	0.861	3.911
	WG	1088	5.839	2.278	0.895	4.074
	NH	7641	3.41	1.954	2.42	13.554
	RWS	295	4.3	2.604	1.487	6.373

H.2.3 *Rutting – Total trafficking*

Split	Authority	Length (km)	mean	Stdev	Skew	kurtosis
[Cat. 1] 0Mil. - 4Mil.	RWS	2023	3.472	1.549	1.572	7.657
	TS	2027	5.67	2.937	0.849	4.026
	WG	1269	6.648	2.402	0.499	3.385
	NH	1053	2.95	1.564	2.322	12.524
[Cat. 2] 4Mil. - 8Mil.	NL RWS	971	4.387	1.84	1.601	7.696
	NH	569	3.299	1.747	2.254	12.458
	WG	314	5.009	1.765	1.145	4.358
	TS	464	5.319	2.859	0.716	2.909
[Cat. 3] 8Mil. - 12Mil.	RWS	603	5.306	2.65	1.698	6.6
	NH	376	3.679	1.965	1.923	8.88
	WG	177	4.94	1.865	1.043	4.253
	TS	244	5.331	2.709	0.635	2.809
[Cat. 4] 12Mil. - 16Mil.	TS	164	4.696	2.422	0.673	2.828
	RWS	365	5.089	2.171	1.524	6.814
	NH	313	3.811	1.881	2.003	9.858
	WG	133	5.51	2.062	1.307	5.003
[Cat. 5] 16Mil. - 20Mil.	NH	181	4.757	2.728	2.113	10.63
	WG	112	5.381	2.047	1.373	5.213
	RWS	278	5.811	2.361	1.049	4.547

H.3 Cracking

H.3.1 Cracking – Age

Split	Authority	Length (km)	mean	Stdev	Skew	kurtosis
[Cat. 1] 0 - 6 yrs.	TS	1011	0.097	0.218	11.226	333.348
	WG	292	0.092	0.204	5.745	53.645
	NH	4253	0.242	1.038	11.392	212.975
[Cat. 2] 6 - 12 yrs.	TS	594	0.19	0.471	12.297	236.02
	WG	233	0.173	0.296	2.938	14.117
	NH	2641	0.54	1.566	7.201	81.769
[Cat. 3] 12 - 18 yrs.	TS	436	0.196	0.488	12.189	270.756
	WG	502	0.195	0.383	4.214	31.228
	NH	1127	0.781	2.022	8.547	116.917
[Cat. 4] 18 - 24 yrs.	TS	330	0.348	0.677	4.624	33.326
	WG	370	0.179	0.397	4.273	27.64
	NH	366	1.532	3.362	4.489	28.963
[Cat. 5] 24 - 30 yrs.	TS	154	0.216	0.515	6.494	69.069
	WG	456	0.245	0.5	4.753	35.964
	NH	586	3.495	5.027	2.519	11.191

H.3.2 Cracking – Material type

Split	Authority	Length (km)	mean	Stdev	Skew	kurtosis
HRA	TS	223	0.295	0.626	5.457	46.842
	WG	158	0.317	0.599	3.726	22.873
	NH	1755	3.145	5.039	2.913	14.11
TSCS	TS	1328	0.181	0.406	12.954	322.512
	WG	1102	0.164	0.345	4.168	27.261
	NH	7749	0.419	1.405	9.437	149.117

H.3.3 Cracking – Total trafficking

Split	Authority	Length (km)	mean	Stdev	Skew	kurtosis
[Cat. 1] 0Mil. - 4Mil.	**TS**	2062	0.184	0.403	11.231	254.352
	WG	1288	0.175	0.34	6.357	94.528
	NH	1080	0.308	1.159	9.008	124.42
[Cat. 2] 4Mil. - 8Mil.	**TS**	471	0.191	0.478	6.286	59.034
	WG	317	0.195	0.519	5.142	36.977
	NH	573	0.477	1.6	7.17	79.681
[Cat. 3] 8Mil. - 12Mil.	**TS**	247	0.217	0.464	5.214	44.935
	WG	178	0.167	0.397	5.591	50.56
	NH	379	0.546	1.675	6.375	56.277
[Cat. 4] 12Mil. - 16Mil.	**TS**	167	0.27	0.727	6.993	70.819
	WG	134	0.253	0.529	3.808	23.804
	NH	316	0.943	2.996	6.412	58.385
[Cat. 5] 16Mil. - 20Mil.	**WG**	113	0.224	0.533	5.268	54.857
	NH	182	1.13	2.64	5.106	40.672

H.4 Texture depth

H.4.1 Texture depth – Age

Split	Authority	Length (km)	mean	Stdev	Skew	kurtosis
[Cat. 1] 0 - 6 yrs.	TS	1011	0.887	0.226	1.268	6.116
	WG	292	1.017	0.235	0.083	2.964
	NH	4253	0.987	0.233	0.652	4.652
	RWS	2938	0.846	0.276	0.233	3.16
[Cat. 2] 6 - 12 yrs.	RWS	2166	0.952	0.232	-0.356	3.851
	NH	2641	1.055	0.251	0.546	4.62
	WG	233	1.064	0.26	0.083	3.355
	TS	594	1.002	0.263	0.727	4.02
[Cat. 3] 12 - 18 yrs.	NH	1127	1.123	0.24	0.537	4.45
	RWS	420	0.964	0.283	0.225	3.378
	TS	436	1.087	0.288	0.368	3.215
	WG	502	1.104	0.292	0.354	3.215
[Cat. 4] 18 - 24 yrs.	TS	330	1.205	0.452	0.7	3.077
	WG	370	1.045	0.276	0.881	4.198
	NH	366	1.171	0.303	0.603	3.848
[Cat. 5] 24 - 30 yrs.	NH	586	1.38	0.426	0.074	2.629
	WG	456	1.18	0.382	0.469	3.438
	TS	155	1.113	0.401	0.864	3.629

H.4.2 Texture depth - Material type

Split	Authority	Length (km)	mean	Stdev	Skew	kurtosis
Asph.	WG	112	1.076	0.25	0.246	3.523
	RWS	313	0.54	0.182	0.627	8.487
HRA	NH	1755	1.367	0.381	0.272	2.673
	WG	158	1.184	0.449	0.593	2.758
	TS	223	1.248	0.431	0.411	2.431
TSCS	TS	1328	1.039	0.269	0.706	3.962
	WG	1102	1.051	0.259	0.524	3.694
	NH	7749	1.035	0.233	0.646	4.542
	RWS	319	0.696	0.208	0.206	3.48

H.4.3 Texture depth - Total trafficking

Split	Authority	Length (km)	mean	Stdev	Skew	kurtosis
[Cat. 1] 0Mil. - 4Mil.	RWS	2206	0.878	0.298	0.166	2.959
	TS	2063	0.986	0.301	1.247	5.563
	WG	1288	1.049	0.283	0.751	5.02
	NH	1080	1.013	0.237	0.748	4.709
[Cat. 2] 4Mil. - 8Mil.	RWS	1055	0.893	0.22	-0.314	3.862
	NH	573	1.046	0.254	0.745	4.533
	WG	317	1.116	0.374	0.383	3.009
	TS	471	1.099	0.356	1.085	4.724
[Cat. 3] 8Mil. - 12Mil.	RWS	640	0.941	0.221	0.019	3.48
	NH	379	1.03	0.249	0.858	5.061
	WG	178	1.108	0.337	0.112	2.541
	TS	247	1.131	0.395	0.81	2.959
[Cat. 4] 12Mil. - 16Mil.	TS	167	1.174	0.471	0.743	2.715
	RWS	408	0.954	0.211	0.314	4.18
	NH	316	1.018	0.31	1.035	4.401
	WG	134	1.23	0.337	0.503	2.922
[Cat. 5] 16Mil. - 20Mil.	NH	182	1.132	0.338	0.827	3.728
	WG	113	1.106	0.322	0.644	3.936
	RWS	298	0.989	0.198	0.007	3.718

H.5 Skid resistance

H.5.1 Skid resistance- Age

Split	Authority	Length (km)	mean	Stdev	Skew	kurtosis
[Cat. 1] 0 - 6 yrs.	TS	1010	0.511	0.071	0.129	3.091
	WG	293	0.539	0.07	0.503	3.413
	NH	4265	0.478	0.061	0.305	4.504
	RWS	3402	0.538	0.053	-0.141	3.303
[Cat. 2] 6 - 12 yrs.	TS	671	0.475	0.071	0.205	3.661
	WG	230	0.546	0.08	-0.545	5.809
	NH	2625	0.464	0.067	0.296	4.033
	RWS	2558	0.517	0.052	-0.077	2.971
[Cat. 3] 12 - 18 yrs.	TS	459	0.478	0.077	0.175	3.757
	WG	491	0.519	0.082	-0.309	4.294
	NH	1125	0.458	0.066	0.75	4.4
	RWS	537	0.499	0.049	0.132	3.465
[Cat. 4] 18 - 24 yrs.	TS	279	0.473	0.077	0.124	3.188
	WG	381	0.564	0.067	0.078	3.21
	NH	383	0.448	0.066	0.371	3.866
[Cat. 5] 24 - 30 yrs.	TS	247	0.454	0.083	-0.046	2.81
	WG	459	0.506	0.081	-0.364	5.587
	NH	577	0.419	0.071	0.377	3.124

H.5.2 Skid resistance – Material type

Split	Authority	Length (km)	mean	Stdev	Skew	kurtosis
Asph.	WG	112	0.539	0.069	0.174	3.446
	RWS	354	0.488	0.061	-0.037	2.908
HRA	TS	224	0.46	0.079	-0.034	3.118
	WG	158	0.56	0.071	0.248	3.412
	NH	1755	0.445	0.076	0.327	3.282
TSCS	TS	1329	0.489	0.076	0.164	3.343
	WG	1102	0.547	0.075	-0.163	4.416
	NH	7749	0.472	0.061	0.429	3.993
	RWS	311	0.492	0.047	0.184	3.85

H.5.3 Skid resistance – Total trafficking

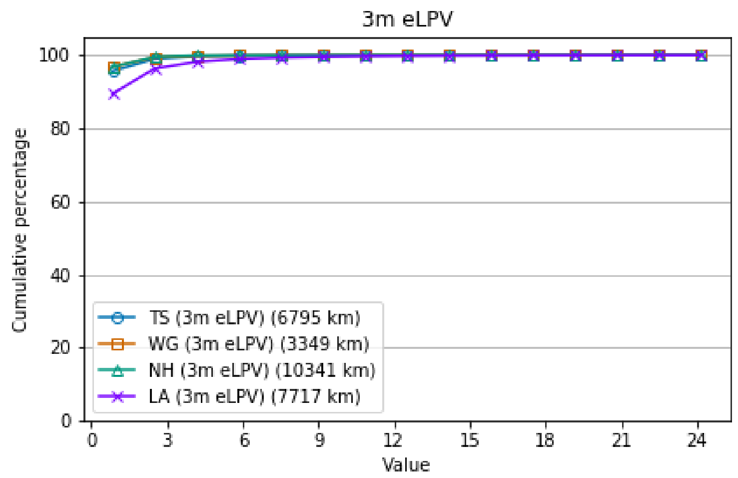
Split	Authority	Length (km)	mean	Stdev	Skew	kurtosis
[Cat. 1] 0K - 2K	TS	2719	0.496	0.077	0.074	3.12
	WG	1776	0.53	0.081	-0.338	4.9
	NH	778	0.484	0.072	0.438	4.193
	RWS	1552	0.522	0.057	-0.208	3.112
[Cat. 2] 2K - 3K	TS	432	0.451	0.071	-0.185	3.845
	WG	286	0.533	0.086	-0.153	2.437
	NH	729	0.463	0.062	0.106	3.48
	RWS	1532	0.528	0.051	-0.142	3.009
[Cat. 3] 3K - 5K	TS	189	0.455	0.053	-0.29	4.342
	WG	112	0.525	0.072	0.527	3.568
	NH	610	0.462	0.068	0.085	4.115
	RWS	1419	0.527	0.058	0.084	2.932
[Cat. 4] 5K - 6K	NH	600	0.464	0.056	-0.056	3.705
	RWS	1193	0.519	0.053	-0.131	2.969
[Cat. 5] 6K - 8K	NH	432	0.457	0.052	-0.162	5.088
	RWS	553	0.524	0.055	-0.127	2.893

Appendix I Results of the local authority comparison

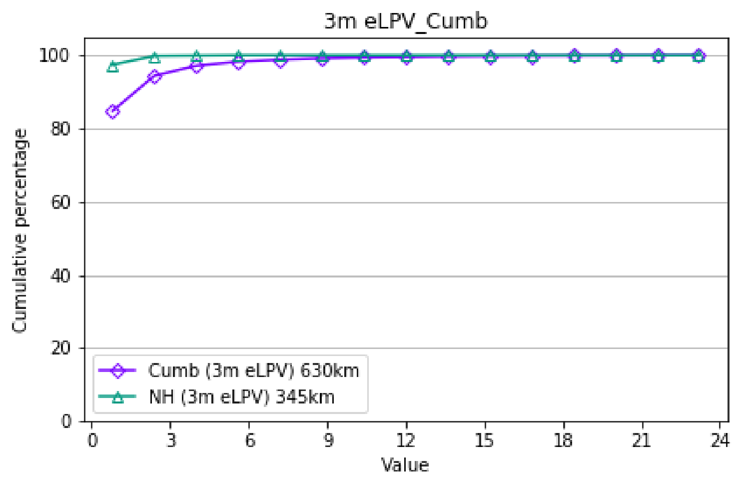
The results of the Local Authority comparison are presented in the following sections as a series of plots for each condition parameter and a table summarising the results of the statistical tests. The plots entitled “whole network” combine all of the Local Authority data into a single network for comparison with the national networks. The National Highways sub-networks are then compared with the Local Authority roads local to that part of the National Highways network, as discussed above.

I.1 3m eLPV

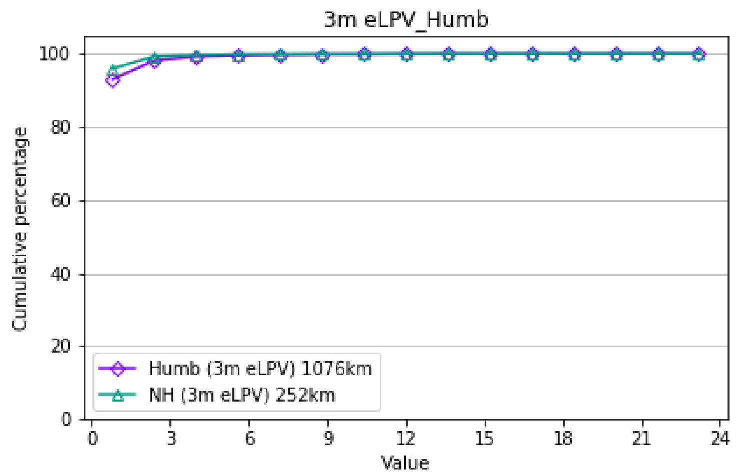
Whole network



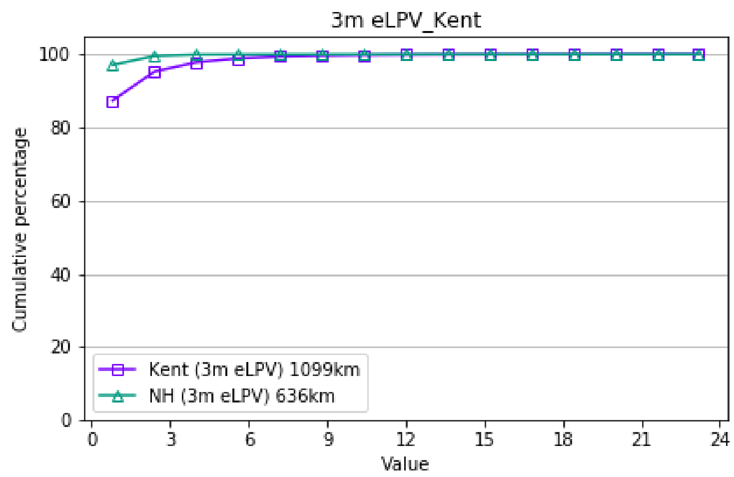
Cumbria



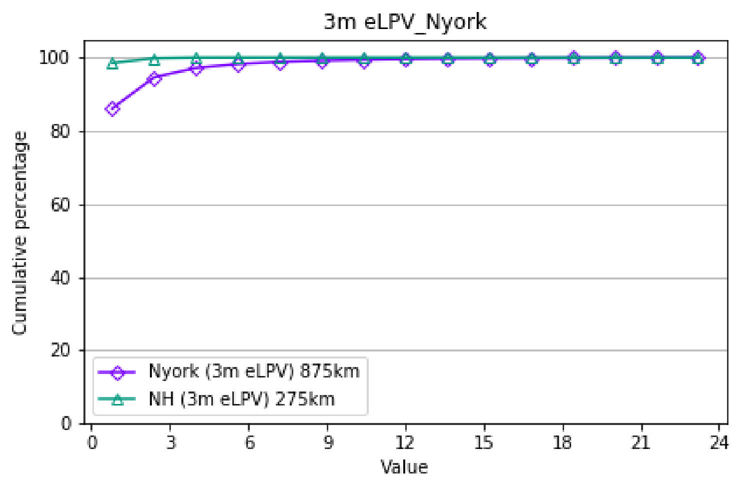
Humberside



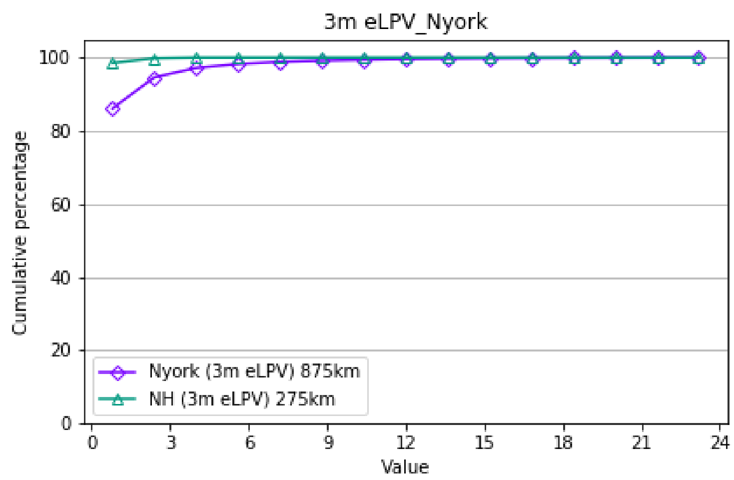
Kent



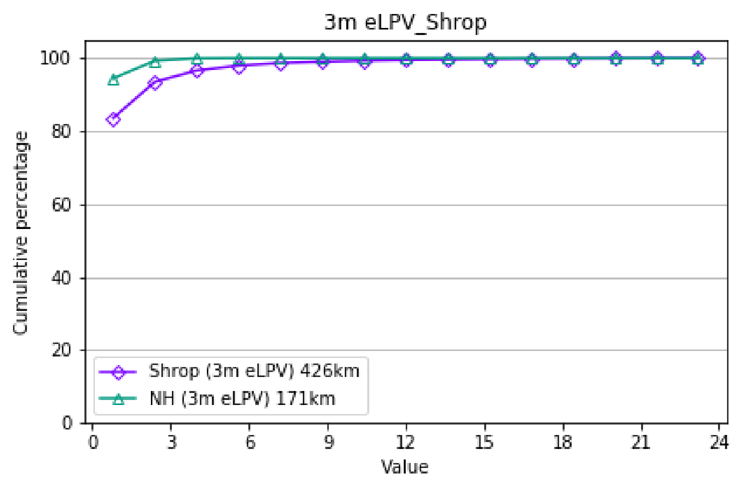
Norfolk



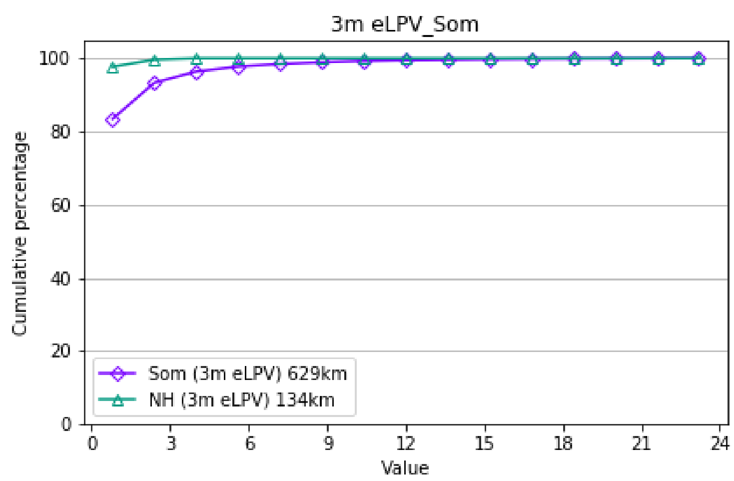
North Yorkshire

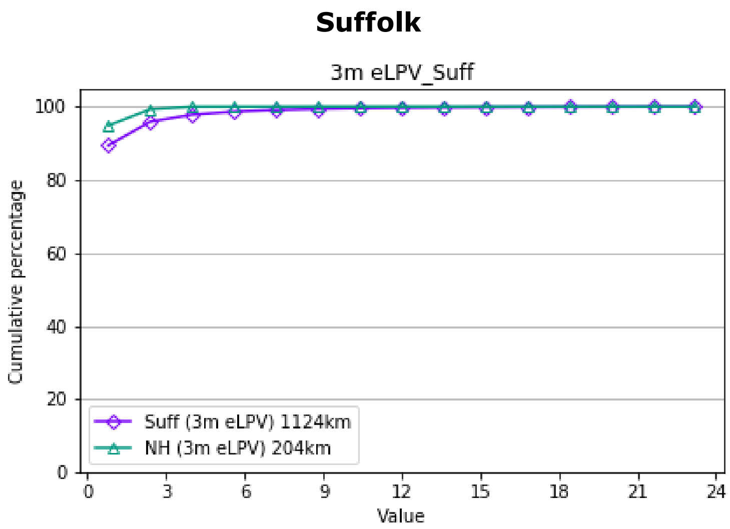


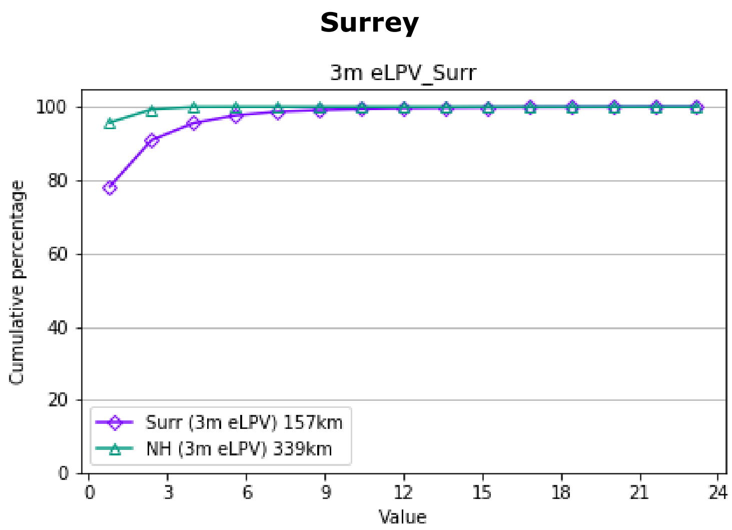
Shropshire



Sommerset



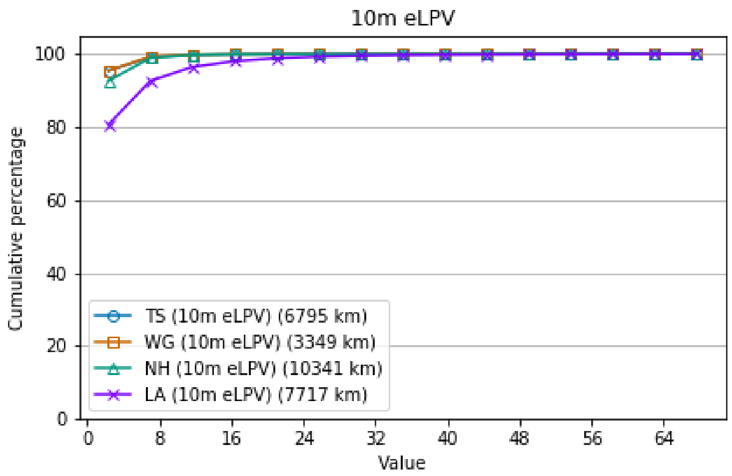




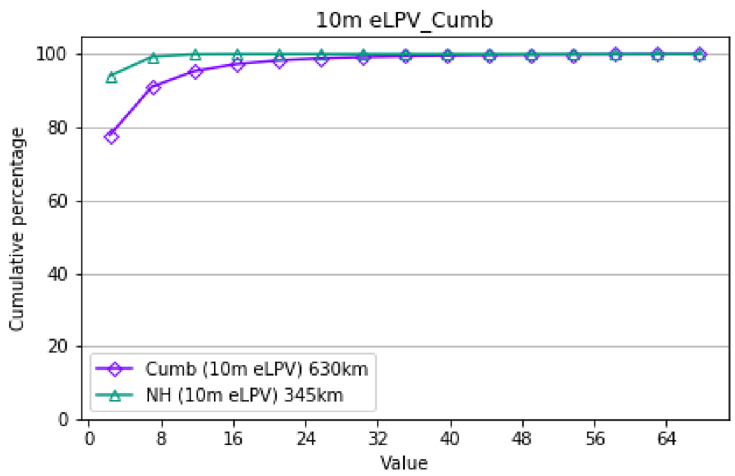
Area	Network	Mean	5th percentile	95th percentile	Standard deviation	Skew	Kurtosis	Effect size
Cumbria	LA	1.118	0.17	3.5	2.505	15.834	457.882	Large
	NH	0.427	0.095	1.35	0.44	3.328	21.102	
Humberside	LA	0.648	0.1	2.56	1.042	14.215	491.337	Small
	NH	0.464	0.11	1.5521	0.636	7.117	90.731	
Kent	LA	0.797	0.07	3.1	1.394	5.682	64.589	Small
	NH	0.435	0.121	1.40335	0.502	6.506	98.084	
Norfolk	LA	0.282	0.08	2.11	0.502	5.33	44.734	Small
	NH	0.625	0.167	1.8142	0.571	3.108	18.052	
North Yorkshire	LA	1.03	0.14	3.41	2.173	11.765	278.799	Large
	NH	0.313	0.08	1.066	0.351	4.356	31.222	
Shropshire	LA	1.146	0.13	3.8805	3.285	51.262	5547.506	Small
	NH	0.56	0.162	1.818	0.559	3.097	16.078	
Sommerset	LA	1.161	0.13	4.01	2.514	13.611	470.998	Medium
	NH	0.418	0.115	1.251	0.429	3.929	26.984	
Suffolk	LA	0.871	0.1	2.87	2.774	43.915	4670.601	Negligible
	NH	0.508	0.125	1.81055	0.582	3.522	24.423	
Surrey	LA	0.899	0.13	4.585	-	-	-	Small
	NH	0.481	0.127	1.5692	0.523	3.447	19.497	

I.2 10m eLPV

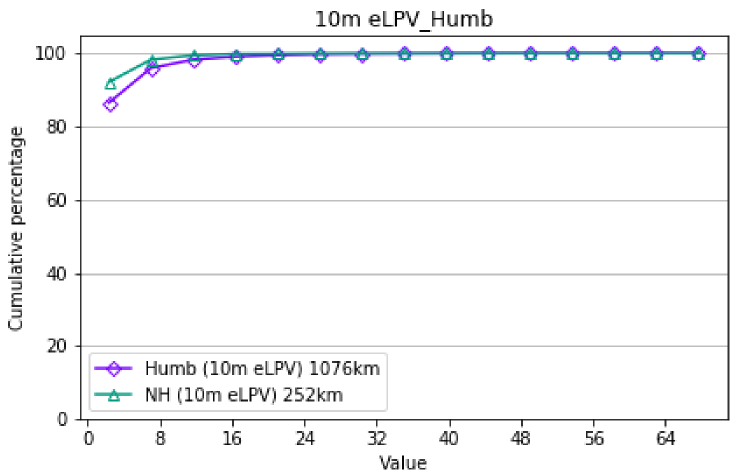
Whole network



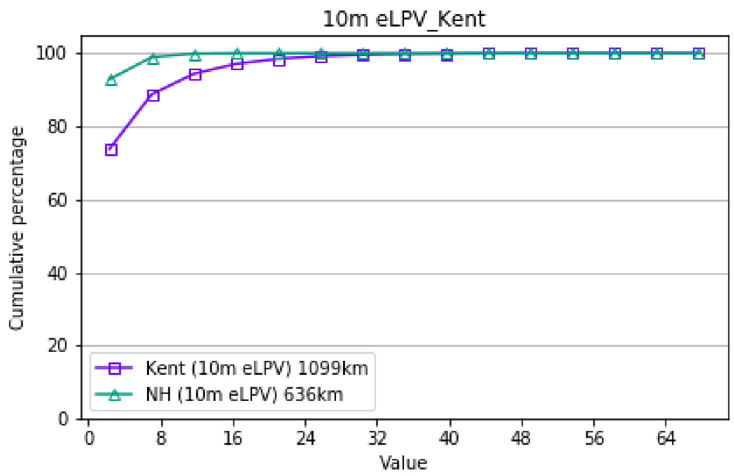
Cumbria



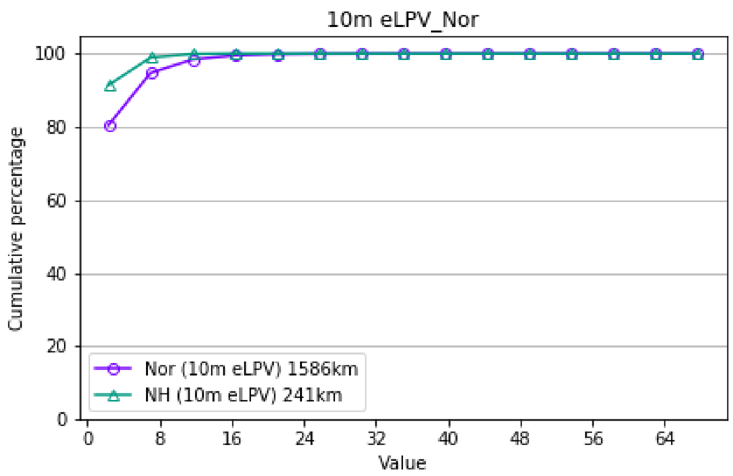
Numberside



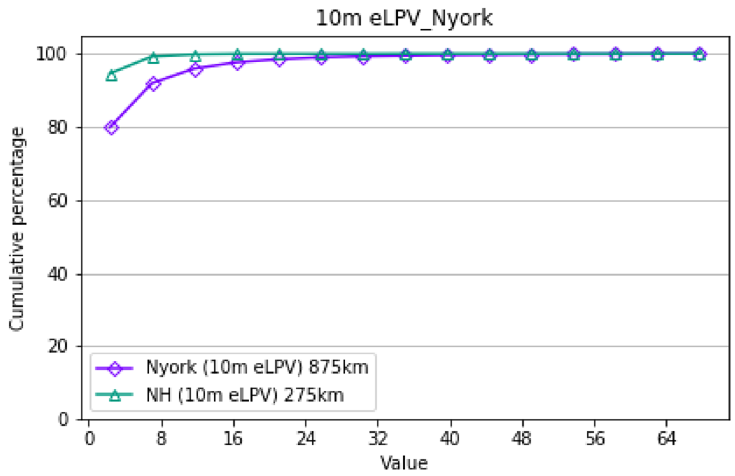
Kent



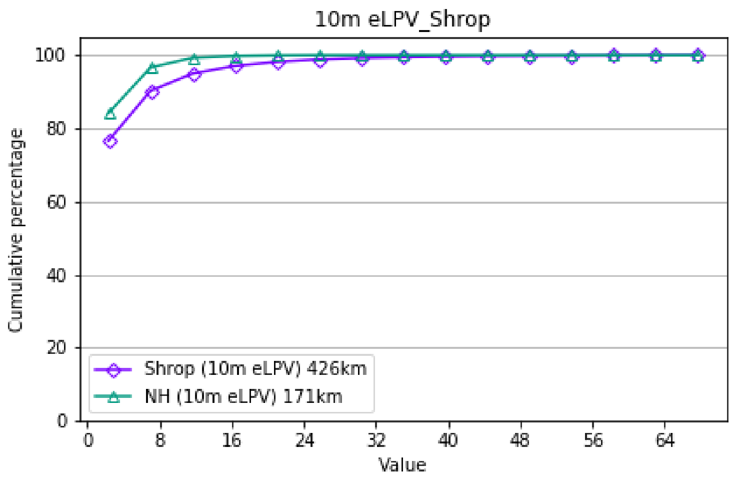
Norfolk



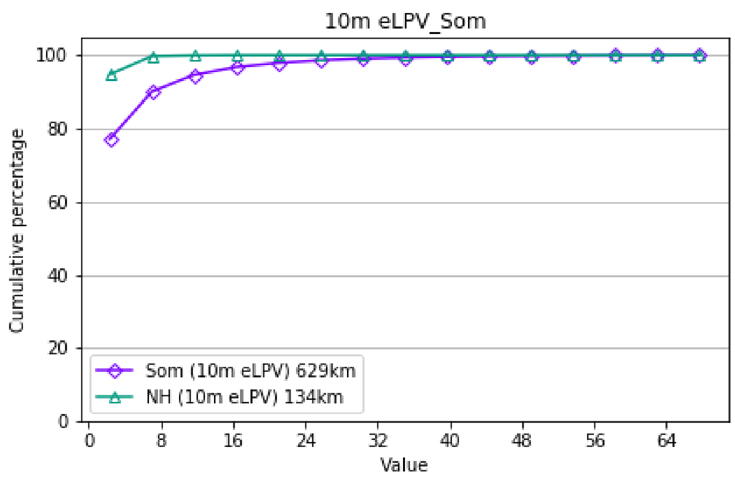
North Yorkshire



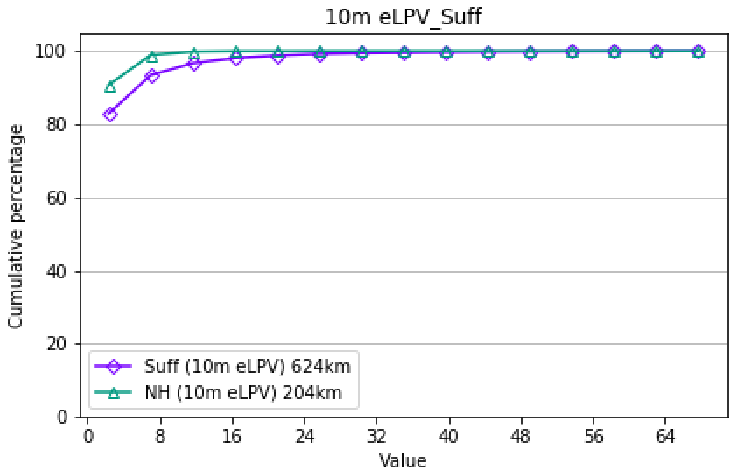
Shropshire



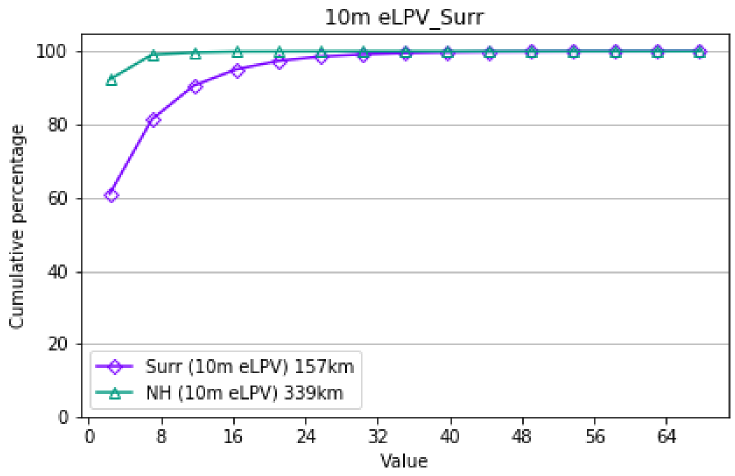
Sommerset



Suffolk



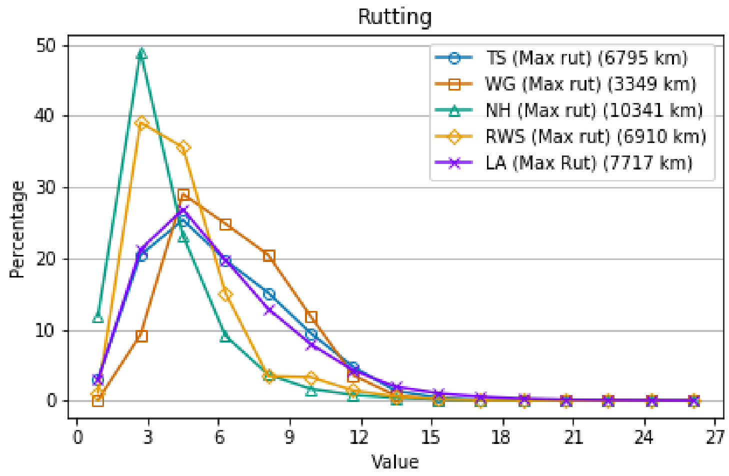
Surrey



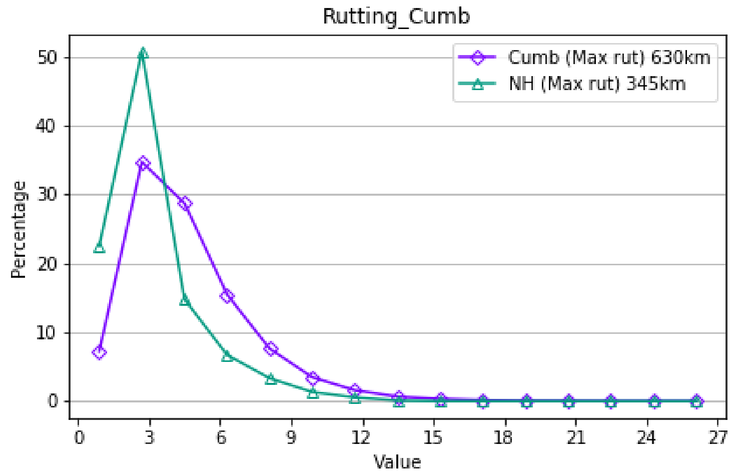
Area	Network	Mean	5th percentile	95th percentile	Standard deviation	Skew	Kurtosis	Effect size
Cumbria	**LA**	3.96	0.45	13.65	6.795	7.081	91.411	Small
	NH	1.894	0.423	5.529	1.663	2.69	13.826	
Humberside	**LA**	2.681	0.41	11.068	3.717	7.091	118.777	Negligible
	NH	2.103	0.474	6.52595	2.181	4.13	31.295	
Kent	**LA**	4.039	0.33	14.843	5.617	3.662	26.383	Small
	NH	2.103	0.596	5.924	1.787	3.109	18.608	
Norfolk	**LA**	1.573	0.443266666	11.017	2.559	4.451	28.747	Small
	NH	2.375	0.7121	6.0743	1.764	2.518	13.177	
North Yorkshire	**LA**	3.661	0.42	12.74	6.344	7.528	105.837	Small
	NH	1.595	0.367	5.918	1.749	4.727	52.172	
Shropshire	**LA**	4.095	0.4	14.351	8	26.469	2049.447	Negligible
	NH	2.85	0.7303	9.1141	2.582	2.629	12.812	
Sommerset	**LA**	4.116	0.39	15.11	7.329	6.829	84.032	Small
	NH	1.841	0.57045	5.017	1.48	2.642	14.162	
Suffolk	**LA**	3.153	0.31	11.02	6.293	16.072	823.16	Negligible
	NH	2.187	0.4545	6.559	1.953	3.176	23.581	
Surrey	**LA**	4.69	0.64	18.654	6.179	3.64	26.738	Medium
	NH	2.137	0.5872	6.1358	1.867	3.834	32.264	

I.3 Rutting

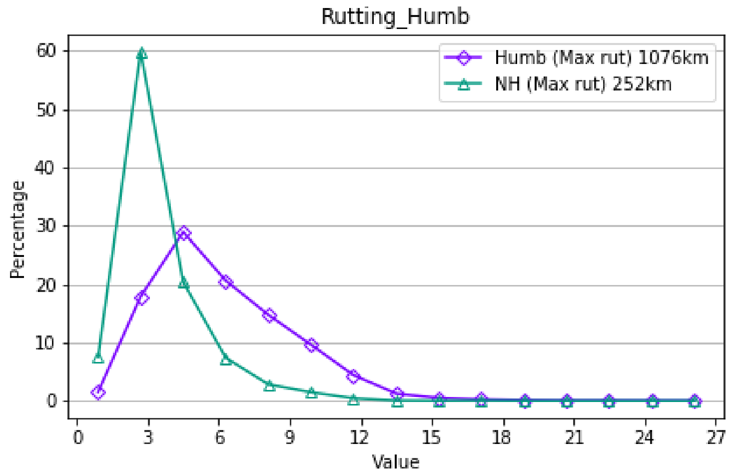
Whole network



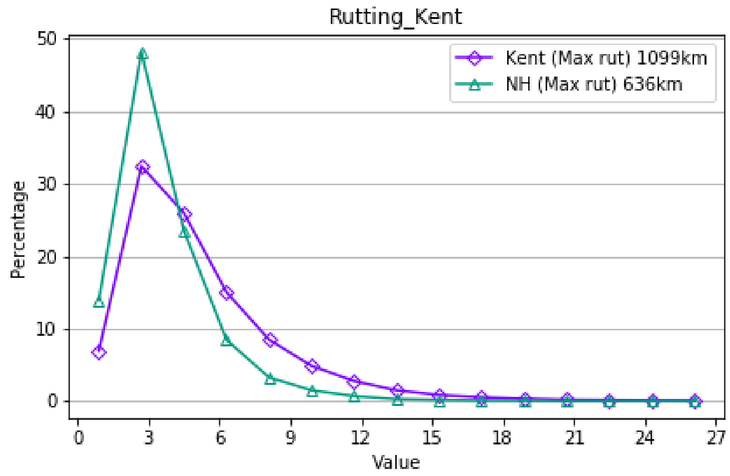
Cumbria



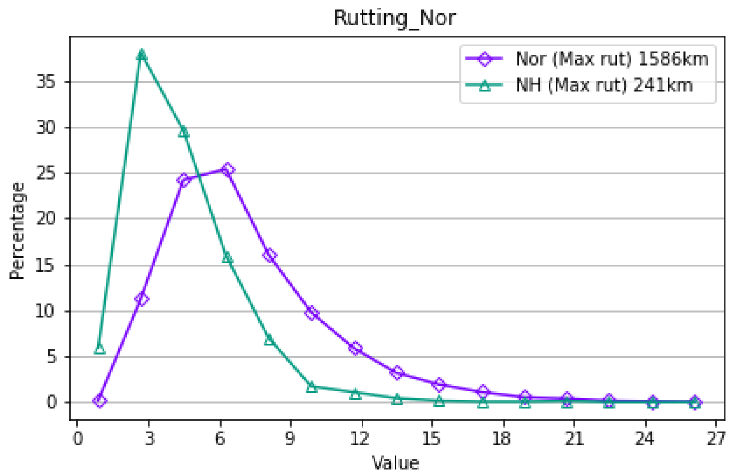
Humberside



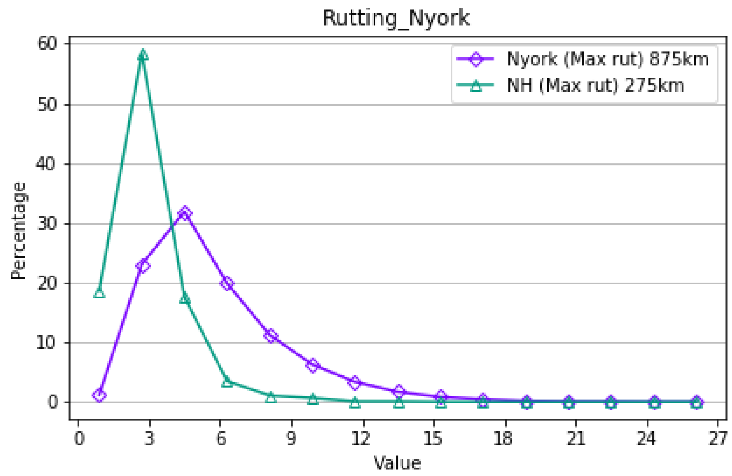
Kent



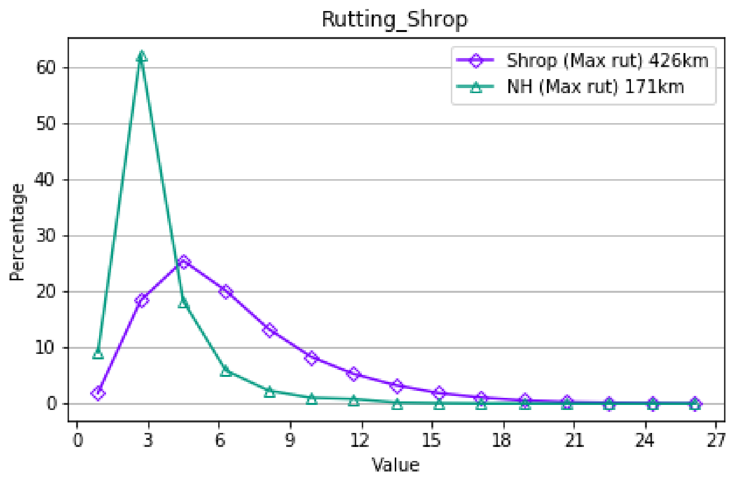
Norfolk



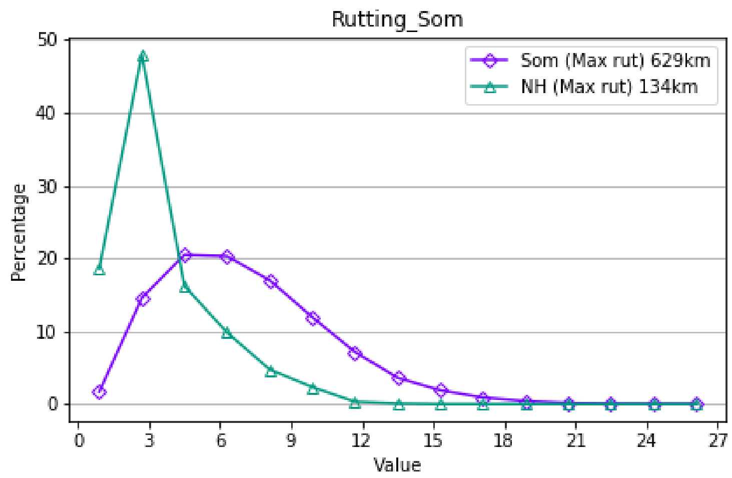
North Yorkshire



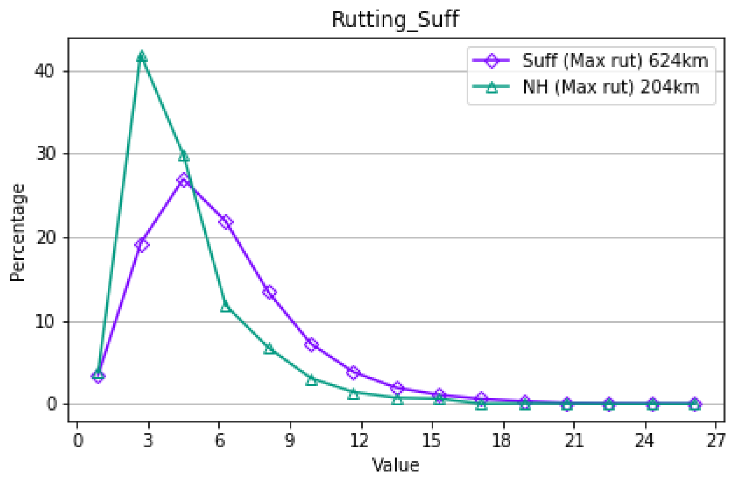
Shropshire



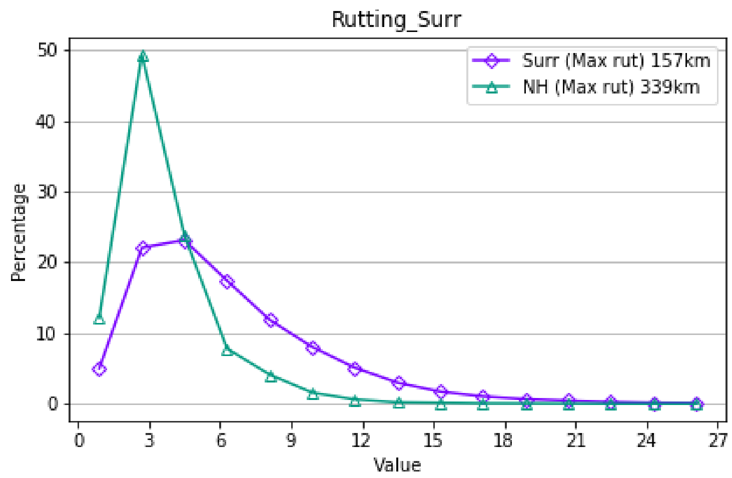
Sommerset



Suffolk



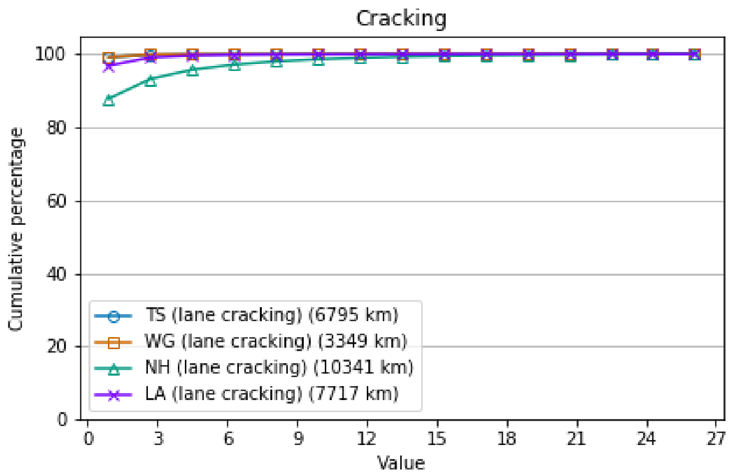
Surrey



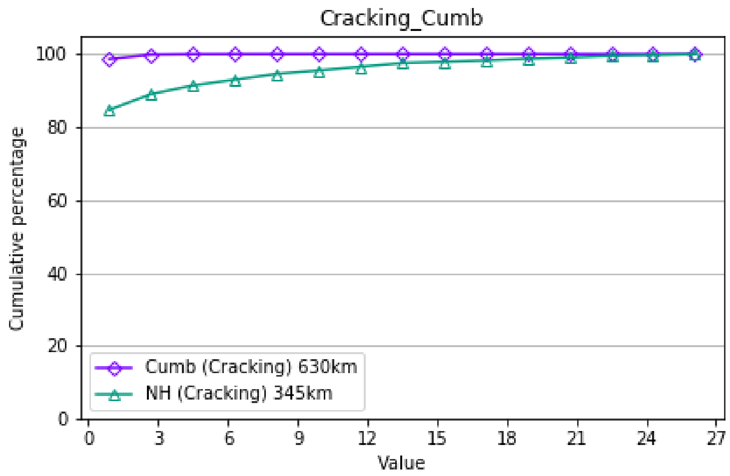
Area	Network	Mean	5th percentile	95th percentile	Standard deviation	Skew	Kurtosis	Effect size
Cumbria	LA	4.56	1.6	9.5	2.564	1.523	6.968	Medium
	NH	3.135	1.17	7.0801	1.919	1.837	7.012	
Humberside	LA	6.067	2.1	11	2.961	1.843	22.632	Large
	NH	3.449	1.6962	7.164	1.774	2.036	8.524	
Kent	LA	5.394	1.6	11.7	5.41	9.695	151.558	Medium
	NH	3.519	1.35235	7.802	2.068	2.176	10.527	
Norfolk	LA	3.657	2.8	13.3	3.526	2.853	11.891	Medium
	NH	4.329	1.772	8.423	2.264	1.803	9.055	
North Yorkshire	LA	5.685	2.4	11.5	2.944	1.529	6.929	Large
	NH	2.872	1.1577	5.57	1.442	2.091	10.773	
Shropshire	LA	6.528	2.3	13.7	3.654	1.377	5.926	Large
	NH	3.32	1.594	7.07	1.776	2.453	11.058	
Sommerset	LA	7.03	2.4	13.5	3.563	1.146	6.678	Large
	NH	3.408	1.3	7.75	2.061	1.476	4.9	
Suffolk	LA	5.928	2	12.2	3.268	1.391	6.149	Small
	NH	4.458	1.9407	9.483	2.461	1.73	6.892	
Surrey	LA	6.327	1.8	14	0.827	-2720	-334889	Large
	NH	3.616	1.4937	7.8931	2.077	2.156	10.375	

I.4 Cracking

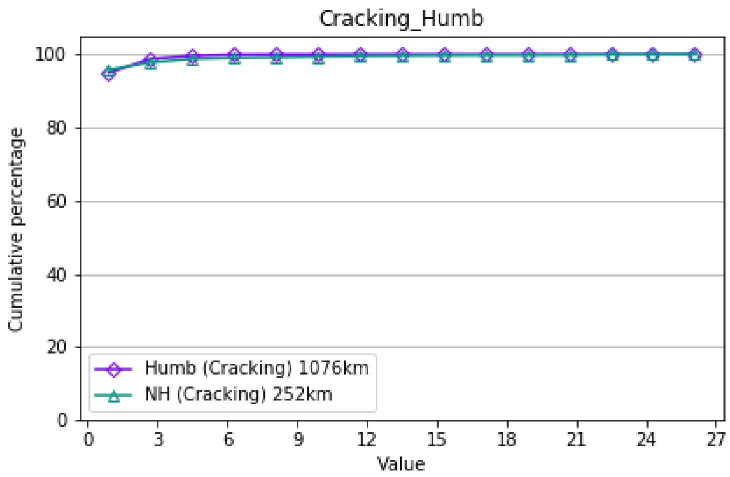
Whole network



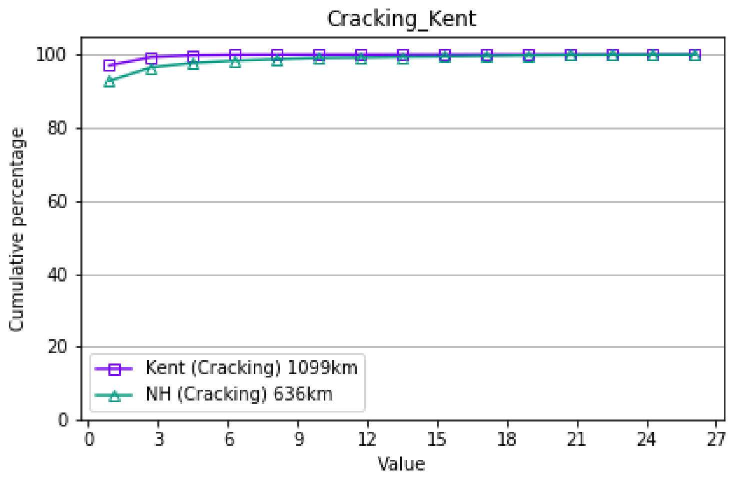
Cumbria



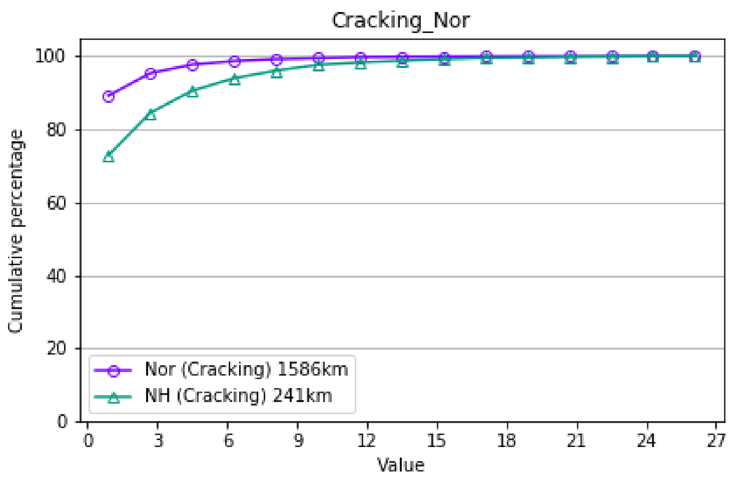
Humberside



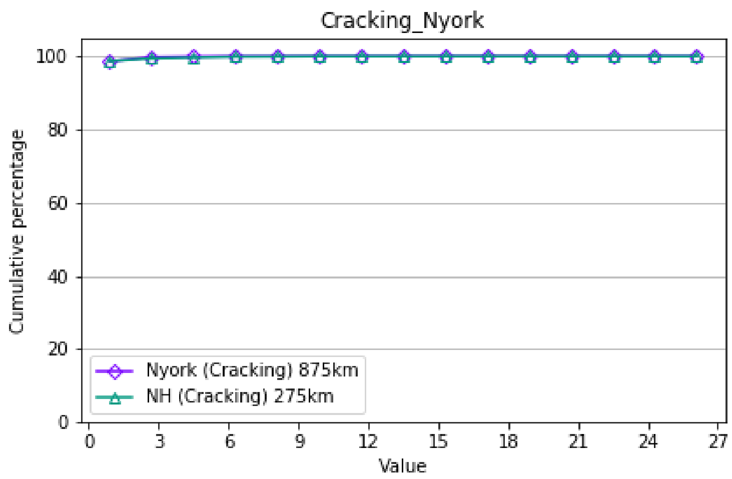
Kent



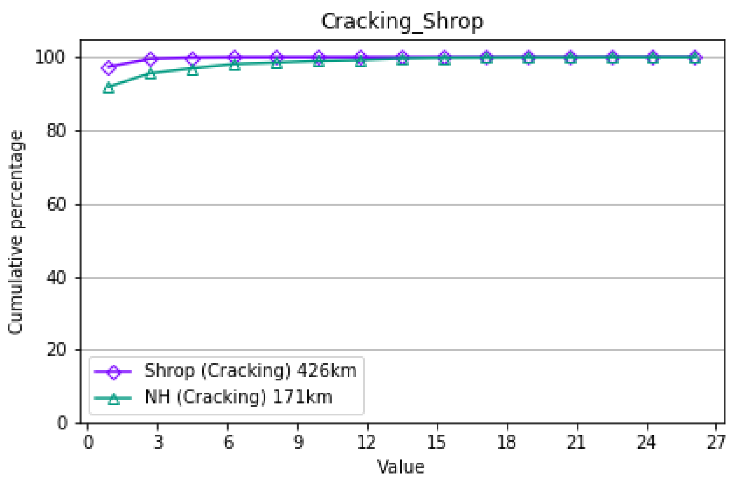
Norfolk



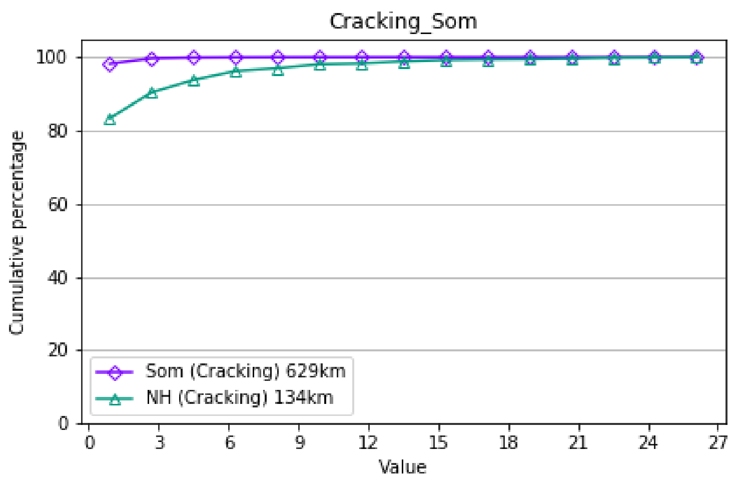
North Yorkshire

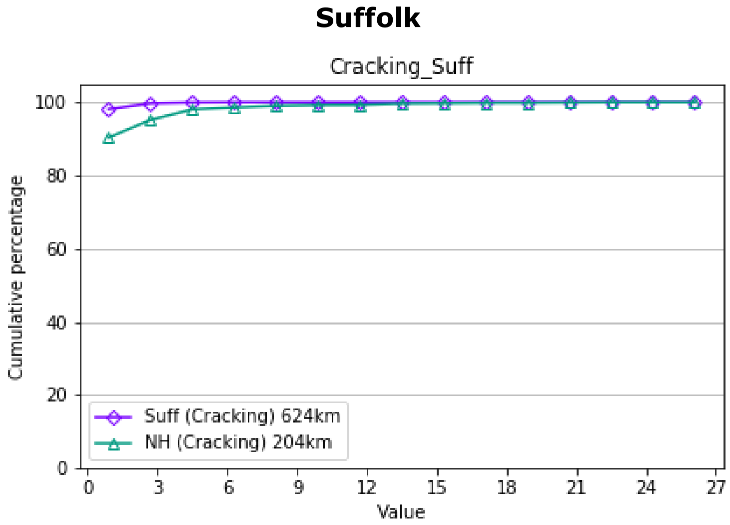


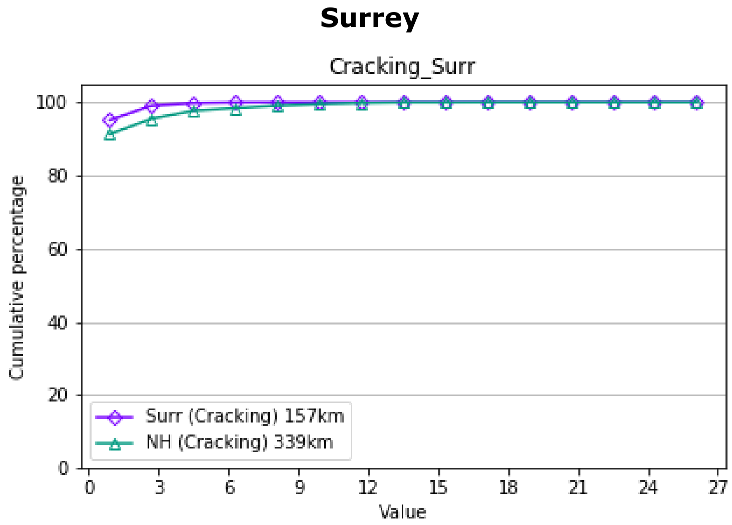
Shropshire



Sommerset



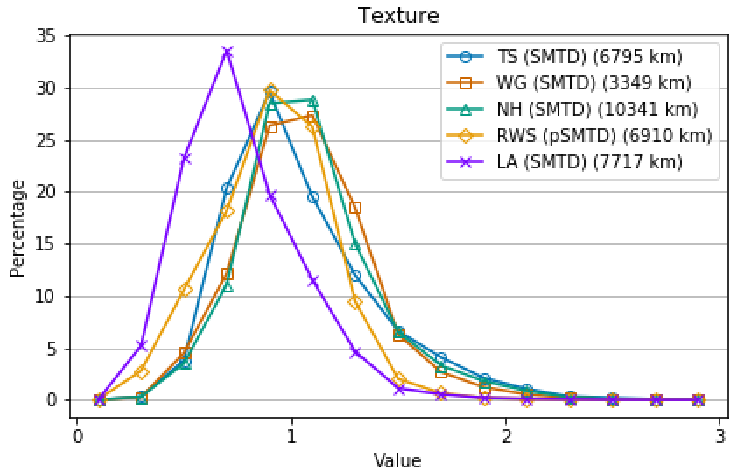




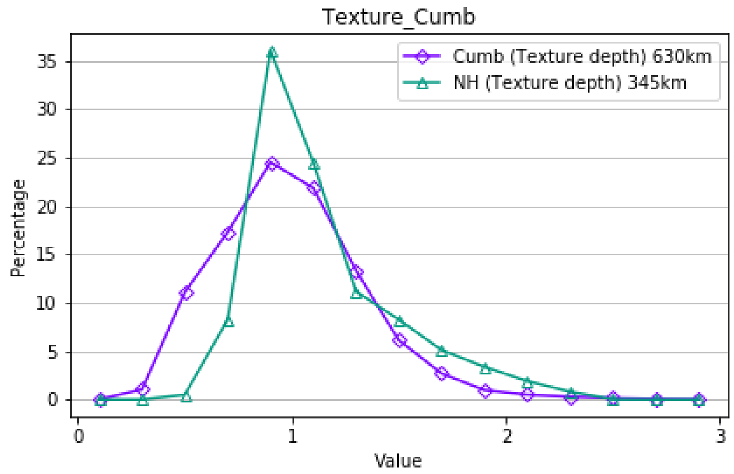
Area	Network	Mean	5th percentile	95th percentile	Standard deviation	Skew	Kurtosis	Effect size
Cumbria	LA	0.151	0	0.9	0.411	5.676	68.939	Negligible
	NH	1.614	0	10.4	4.651	4.161	22.595	
Humberside	LA	0.094	0	1.8	0.455	8.718	110.924	Medium
	NH	0.357	0	1.4	1.612	9.51	114.36	
Kent	LA	0.196	0	1.3	0.609	6.233	67.461	Small
	NH	0.55	0	2.8	1.986	7.175	66.262	
Norfolk	LA	0.344	0	4.0875	1.406	12.98	352.545	Negligible
	NH	1.699	0	7.7	3.147	3.323	17.43	
North Yorkshire	LA	0.13	0	0.8	0.425	7.128	93.358	Small
	NH	0.143	0	0.8	0.567	9.724	128.187	
Shropshire	LA	0.21	0	1.1	0.562	5.501	54.251	Small
	NH	0.695	0	3.025	2.384	8.151	97.138	
Sommerset	LA	0.167	0	0.9	0.514	8.323	144.422	Negligible
	NH	1.24	0	6.4	3.502	5.462	41.88	
Suffolk	LA	0.149	0	0.9	0.478	5.989	56.697	Small
	NH	0.622	0	3.67	1.894	6.731	66.028	
Surrey	LA	0.295	0	1.7	0.751	4.657	38.242	Small
	NH	0.549	0	3.1	1.558	4.809	30.852	

I.5 Texture Depth

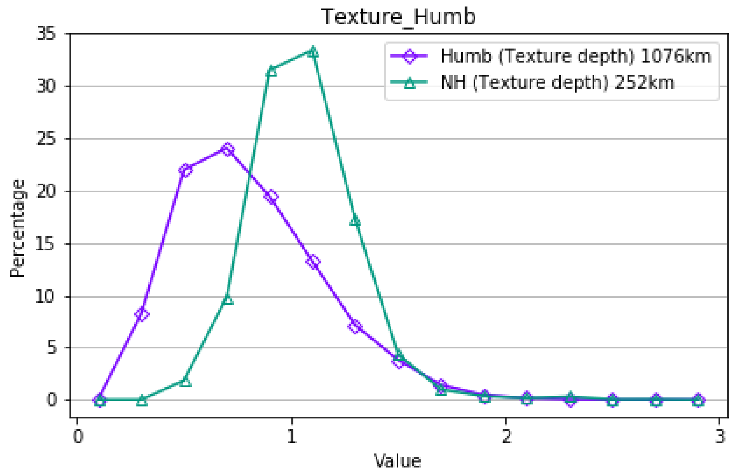
Whole network



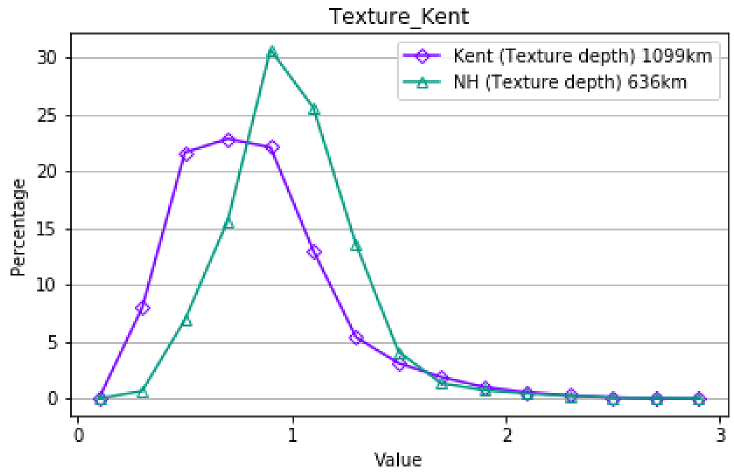
Cumbria



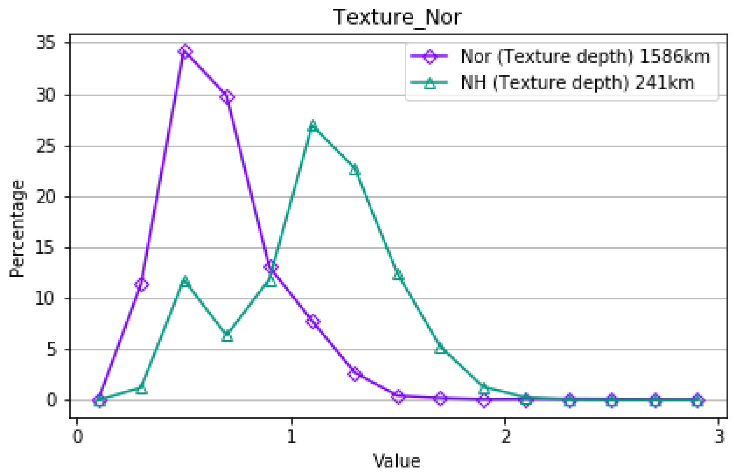
Humberside



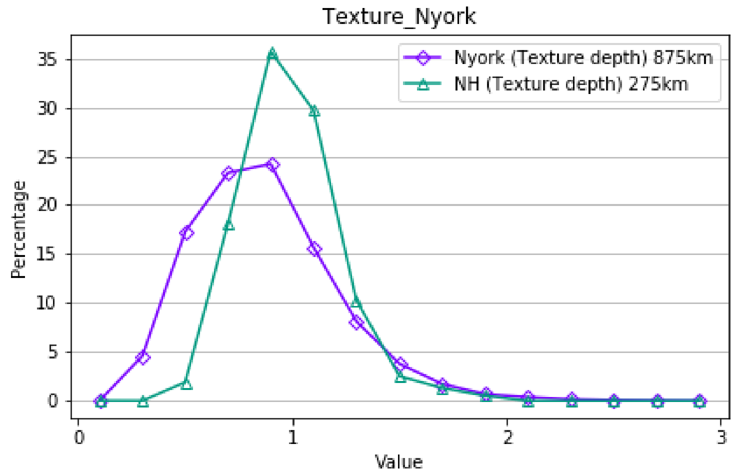
Kent



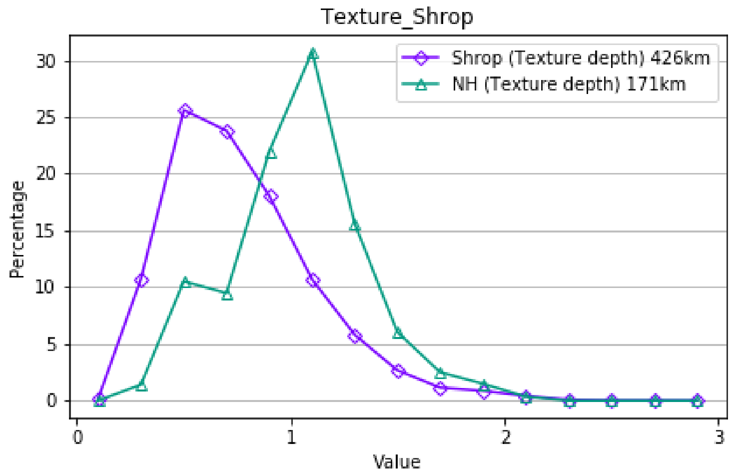
Norfolk



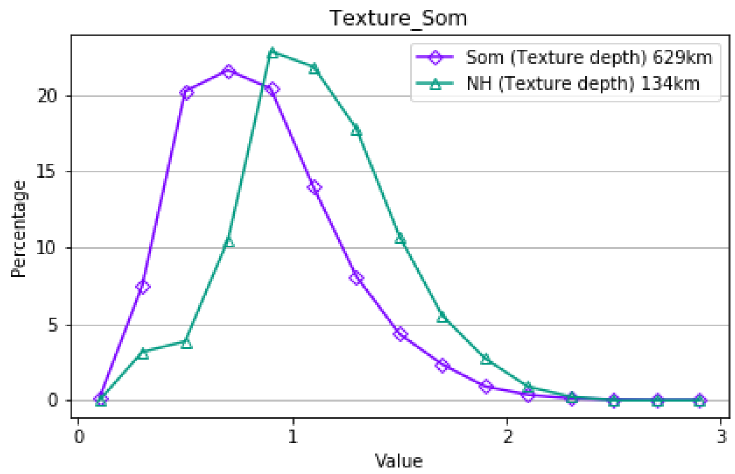
North Yorkshire

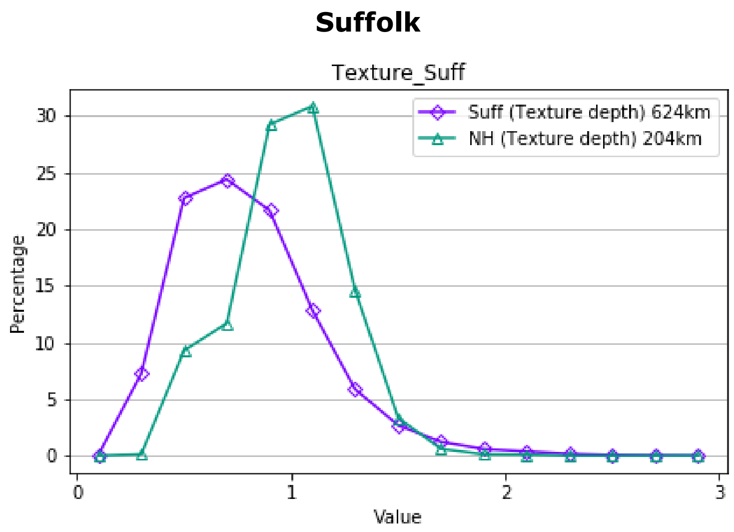


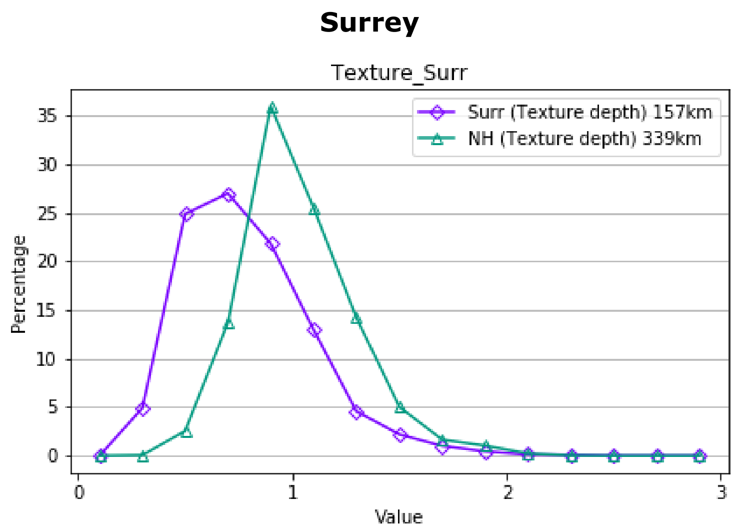
Shropshire



Sommerset



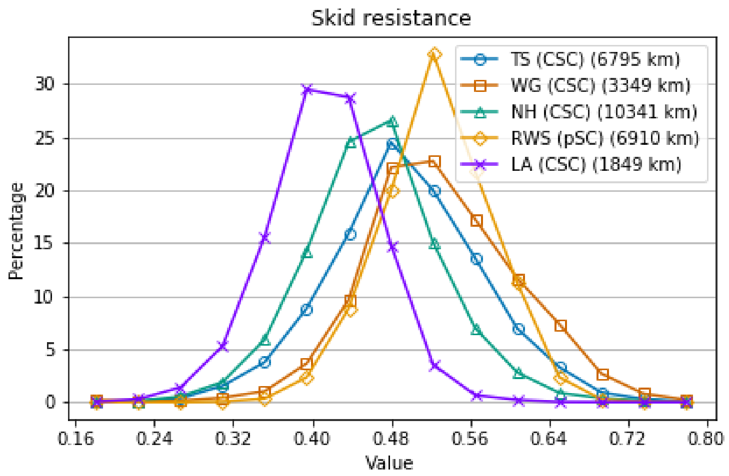




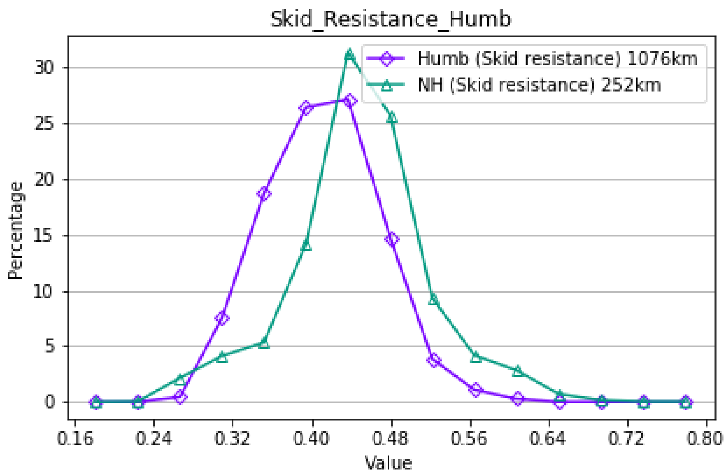
Area	Network	Mean	5th percentile	95th percentile	Standard deviation	Skew	Kurtosis	Effect size
Cumbria	**LA**	0.991	0.5	1.58	0.343	0.967	6.071	Small
	NH	1.133	0.753	1.827	0.339	1.221	4.136	
Humberside	**LA**	0.26	0.34	1.43	0.365	2.51	7.297	Small
	NH	1.053	0.671	1.415	0.238	1.01	6.987	
Kent	**LA**	0.831	0.35	1.51	0.36	1.222	5.259	Medium
	NH	0.995	0.5305	1.461	0.289	0.822	5.328	
Norfolk	**LA**	0.349	0.31265	1.146	0.305	2.631	10.136	Large
	NH	1.11	0.492	1.63435	0.345	-0.227	2.683	
North Yorkshire	**LA**	0.872	0.4	1.48	0.334	0.915	4.622	Small
	NH	0.99	0.648	1.40525	0.223	0.72	4.26	
Shropshire	**LA**	0.768	0.33	1.41	0.343	1.081	4.69	Large
	NH	1.031	0.50475	1.53125	0.316	0.209	3.28	
Sommerset	**LA**	0.851	0.35	1.53	0.368	1.046	6.417	Medium
	NH	1.109	0.516	1.7141	0.357	0.276	3.14	
Suffolk	**LA**	0.805	0.36	1.42	0.337	1.031	4.947	Medium
	NH	0.989	0.538	1.388	0.254	0.054	3.095	
Surrey	**LA**	0.78	0.4	1.33	0.311	1.305	5.102	Large
	NH	1.028	0.63	1.4652	0.258	0.813	4.292	

I.6 Skid Resistance

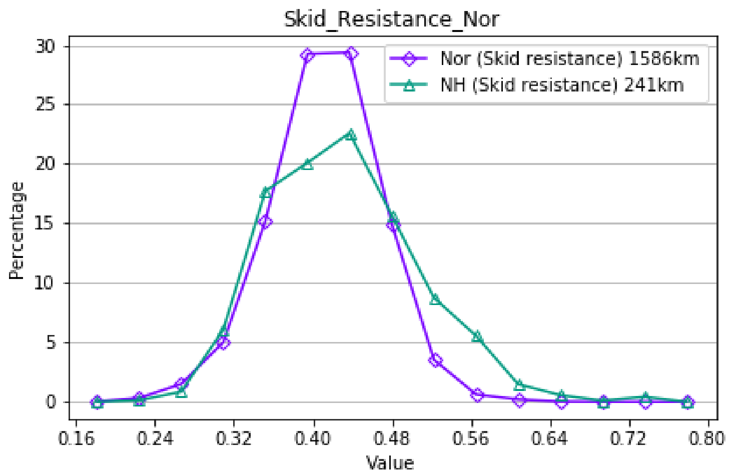
Whole Network



Humberside



Norfolk



Area	Network	Mean	5th percentile	95th percentile	Standard deviation	Skew	Kurtosis	Effect size
Humberside	LA	0.42	0.33	0.51	0.099	4.038	16.616	Large
	NH	0.449	0.32835	0.576	0.069	0	4.021	
Norfolk	LA	0.408	0.31	0.502	0.055	0.093	3.669	Negligible
	NH	0.431	0.322	0.56835	0.076	0.59	3.593	

Benchmarking the condition of highway networks

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