Transport Research Laboratory

NSSRG Phase 2 Summary Report

by M G Evans

CPR726

CLIENT PROJECT REPORT

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by M G Evans (TRL)

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Contents

Executive summary

Phase 2 of the NSSRG research programme was commissioned in 2005, following the completion of Phase 1, and completed in 2009. The work included the undertaking of road trials to investigate the spreading performance and effects of trafficking on de-icers, a review of residual salt measurement techniques, investigations into the dissolution rates of de-icers, an investigation into practices of winter maintenance on footways and cycleways and laboratory trials of the effects of salt application on skidding resistance.

As a result of the work carried out during Phase 2, the following reports were produced and are currently available to download from the members' area of the NSSRG website:

Winter service of footways and cycleways (TRL Report No. UPR IE/014/07)

Review of residual salt measurement techniques (TRL Report No. UPR/IE/128/06)

Salting trials on the A460 Lodge Lane, Staffordshire (TRL Report No. UPR IE/132/07)

Dissolution rates of de-icers (TRL Report No. CPR575)

Skid resistance of de-icers (University of Ulster, HERG Report No. 07348)

Review of salting trials (TRL Report No. CPR574)

The Review of Salting Trials in itself provides analysis and comment on much of the work carried out in Phase 1 and Phase 2 on salt spreading trials.

In addition, during the period of Phase 2 of the NSSRG research programme members such as Transport Scotland, The Highways Agency, Staffordshire and East Sussex county councils separately funded trials and made the results available to the NSSRG. The Highways Agency additionally commissioned TRL to carry out performance trials of de-icers using the Agency's new fleet of spreaders, and made the results of those trials available to the NSSRG. These are available to download from the NSSRG website in the following report:

Salting trials on the M62 at Goole (TRL Report No. UPR/IE/150/06)

The Executive Summaries from all the reports produced during Phase 2 have been reproduced in this document, to bring the main findings together in one easily accessible document for the benefit of the NSSRG membership.

The research carried out in Phase 2 represents a valuable body of work and, in conjunction with the work carried out in Phase 1 and on behalf of the Highways Agency, will inform Phase 3 of the research programme. During Phase 3, the NSSRG will expand its remit to cover all aspects of winter service for carriageways, footways and cycle facilities in the UK. This expansion in the aims has also been reflected in the renaming of the group, as the 'National Winter Service Research Group' (NWSRG).

1 Introduction

The Executive Summaries from all the reports produced during Phase 2 of the NSSRG research programme have been reproduced in this document, to bring the main findings together in one easily accessible document for the benefit of the NSSRG membership.

2 Winter service of footways and cycleways

The research described in this report was undertaken as part of the National Salt Spreading Research Group (NSSRG)'s Phase II Research Programme. The aims of this initial study in this topic area were to review the footway and cycleway winter treatment practices currently established by UK and certain other international highway authorities, to review and evaluate the effectiveness and suitability of products and, where possible and appropriate, to comment upon and make recommendations regarding these issues to NSSRG members.

From the review of current policies and practices regarding the provision of winter service on footways and cycleways undertaken as part of this work, it is evident that the majority of UK highway authorities have clearly defined aims and objectives for their winter service provision on footways and cycleways. It seems that, for the most part, these policies are being relatively consistently applied within each authority's administrative area.

It is also clear that the majority of authorities have considered and defined the prioritisation principles they apply to the winter treatment of their footway and cycleway networks (as well as their carriageways) and that a number of authorities are operating policies whereby precautionary salting operations on certain high priority footways are being considered on a day to day basis throughout the winter months.

However, the great majority of footways across the UK are not subject to such considerations and it appears that footway and cycleway treatments often differ markedly from one administrative area to another, without this relating to a material change in risk to the travelling public.

It is therefore considered to be important that, when reviewing their winter service provision for footways and cycleways, liaison should take place between neighbouring authorities with a view to improving consistency for the travelling public.

Specific findings from the survey of members' policies include:

- 29% of the members who replied include precautionary salting of footways in their winter service policy. However, this relates to only a small proportion of the footways within each authority's area and is mostly performed in town centres. The great majority of authorities reactively treat a larger network of footways and cycleways when there is a prolonged frost or as a result of snowfall.
- All the authorities use sodium chloride based de-icers. This is mostly in the form of rock salt, but some use marine salt, salt treated with additives (examples including 'Safecote' and 'Eco-Thaw') or brine. A few authorities use other de-icers such as glycol, urea and potassium acetate at specific locations.
- Priorities for footway and cycleway treatment include town centres, old people's homes, schools, hospitals, steep gradients, railway stations, council buildings, emergency services and bus routes. One authority is trialling a quadrant approach for cycleway treatment, ensuring that a route from each quadrant of a town to the town centre is treated.
- The mechanical application of de-icers on footways is increasing. This is either with a push barrow type spreader or a trailer pulled by mini-tractor or quad bike. Most of the authorities that consider precautionary salting on footways use mechanical methods. The spread rates utilised are similar to those on

carriageways, ranging from 15g/m2 to 25g/m2 for precautionary treatments and 10 to 50g/m2 for reactive treatments.

- The proportion of the winter service budget spent on footways and cycleways is low. In 2005/2006, those precautionary treating spent 0.5 to 20% (the highest being TfL), those reactively treating spent 0 to 11%.
- Treating footways can be resource intensive, but mechanical methods can reduce the costs and time involved. The number of turn-outs for footways is normally significantly less than that for carriageways, which is considered likely to result from the differing trigger conditions for treatment.
- At present, the number of claims relating to ice on footways is small. However, the full effect of the 2003 addition to the Highways Act might yet to be felt.

It is recommended that highway authorities undertake regular reviews of their winter service policies and systems for footways and cycleways. These reviews should consider the latest available technologies and materials to assist in providing the service, as well as developments in case law in this area, and/or any other information available regarding public expectation regarding this issue.

It is considered that authorities should clearly define and set-out their aims and objectives for winter service provision on footways and cycleways, as well as the prioritisation principles that apply to their network. The policies should be rigorously and consistently applied across the network under the control of the highway authority, and it is recommended that authorities liaise with their neighbours and openly discuss these issues in other arenas, with a view to improving consistency across administrative boundaries.

The results of this study indicate that the most cost effective de-icer for the majority of footway and cycleway applications remains sodium chloride, there being indications that this may be most effective for footway treatments in the form of brine, rather than in solid form. However, it is recognised that this may well not be the de-icer that provides 'Best-Value' and it is considered that further work would be necessary in this area to determine the most cost-effective de-icer(s) specifically for footways and cycleways.

Application using mechanical means provides a more homogenous and controlled spread of de-icer than hand spreading. This also tends to speed up application, as well as reducing the costs and labour issues associated with footway and cycleway treatment.

It is considered that further work would be required in this area in order to evaluate the risks posed to pedestrians and cyclists by icy footways and cycleways, the effectiveness of treatments to reduce those risks, the most appropriate timing for such operations and the best materials and application methods to use.

3 Review of residual salt measurement techniques

This report has been prepared as part of the Phase II Research programme of the National Salt Spreading Research Group (NSSRG).

Highway authorities are required to spread de-icer onto the highway at levels sufficient to prevent ice and snow related accidents. However, due to a number of factors relating to the weather and traffic volumes, residual de-icer levels reduce with time following application. The de-icer must then be re-applied to maintain sufficient levels for frost/ice prevention. It is difficult to predict when re-application is required because of the variability of salt dispersal with traffic flow, weather and other road conditions. The decrease in de-icer concentration will vary from one place to another across the network. For this reason, authorities have sought knowledge of the residual de-icer levels on the road network and the ability to monitor its distribution and change with time.

Currently, there appears to be no simple and reliable method of measuring residual de-icer levels on the surfaces of highways. Winter maintenance operators are therefore currently required to use their judgement combined with the weather and traffic information available to them to gauge the correct time and application rates for re-treatment.

This report reviews the currently available technology for measuring residual de-icer levels and the methods that are being developed. Some alternative methods of gauging re-treatment time are discussed; for example, methods of determining the presence of frost and ice on the road surface and the monitoring of friction levels, including roadside remote systems monitoring surface condition using infra-red light.

Passive and active salt sensors that can be embedded in the road surface have been reviewed, together with research and developments in mobile and portable methods. The prospects for the use of spectroscopic measurements of salt concentration in-situ have been included.

Road weather information systems and research leading to simple models for the prediction of rates of salt dissipation have been reviewed.

It has not been possible to find a reliable method of measuring residual salt on the road surface that would function under all conditions. Current embedded road sensors have the limitations described and are considered in the research reviewed to be unreliable, although the active sensors in principle should overcome this to some extent.

Static and portable methods of measuring surface condition are in use. These in general do not measure residual salt. However there is a considerable body of opinion that detection of the onset of ice formation, either by mobile friction measurements or by spot surface measurements of condition and temperature, can be a useful input to road condition models and thus the decision making process. There is, however, uncertainty as to whether surface condition measurements can provide enough advanced warning to be useful in the triggering of treatment.

Remote sensors which simultaneously measure ice film thickness and surface temperature hold out the prospect of being able to directly measure the freezing point when the temperature falls from above to below the current freezing point, or the reverse. The temperature measured at the first detection of ice (or the last in the case of temperature rise) is expected to provide a good indication of the freezing point of the salt solution on the surface at that time. However, if the objectives of anti-icing measures are met, no freezing should ever be detected. This technology might best be seen as providing a check on the effectiveness of treatment, at critical locations on the network.

Portable methods are believed to be too labour intensive for routine use. However, mobile systems that can be mounted on winter maintenance vehicles can gather data during normal operations, which reduces or eliminates extra labour, but such systems mounted on salt-spreading vehicles can only give information (e.g. ice presence and skidding resistance) immediately before spreading, unless extra trips are made for survey purposes.

There may be potential in the fluorescence methods reviewed, but these are all currently severely handicapped by the very small effective sample size available on the road surface. There could be value in trials of the most promising of these, the man portable LIBS system.

The mobile method of measuring salt concentration using an active Peltiér sensor shows promise as this can potentially give intermittent averages over the whole of a patrolled network, at traffic speed. This is under active development by Combitech/Saab in Sweden.

The results of the small amount of modelling of the rate of salt dissipation from the road surface which has been carried out suggest that such a model would be complex. It also appears that dissipation is generally so fast that applying effort to the determination of residual salt may not be cost-effective.

Suggested future work includes measurements of the rate of dissipation of salt concentration at a number of sites to determine both the effects of the initial salt concentration and the effect of different locations and conditions.

4 Salting Trials on the A460 Lodge Lane, Staffordshire

Salting trials, jointly funded by Staffordshire County Council, the NSSRG, Transport Scotland and East Sussex County Council, were carried out on the A460, Lodge Lane, in Staffordshire during the period April to June 2007. The trials were designed to evaluate and compare the performance of untreated salt, pre-wetted salt and treated salt. The main objectives were to determine:

- The spread rate and spread pattern for 6.3mm dry untreated rock salt, 6.3mm pre-wetted rock salt and 6.3mm rock salt treated with Safecote.
- Whether any improvements in the spreading technique can be achieved by changes to the calibration method for the different salts, and determine any practical problems associated with their spreading.
- The residual salt levels 12 hours (following the morning rush hour), 24 hours and 48 hours after spreading.

The target mix proportions for the pre-wetted salt were 70 per cent dry salt: 30 per cent brine by weight. The target brine concentration was 26 per cent. The target mix proportions for the treated salt were 97 per cent dry salt: 3 per cent Safecote by weight.

Lodge Lane is a single carriageway with two 4m wide lanes, each with a 1m wide hard shoulder to a raised kerb. The surfacing is stone mastic asphalt and, therefore, negatively textured. The de-icers were spread at a target rate of 20g/m² with the spreader travelling in the eastbound lane (lane 1) and set up for two-lane asymmetric spreading over an 8m spread width. This particular spread rate was chosen because it is one of the rates often used for precautionary treatment and was sufficiently high to facilitate the measurement of residual salt levels after trafficking. The spreaders were set up and operated by Staffordshire County Council staff.

The site used for the trials was designed to be of sufficient length to enable separate de-icers to be applied to straight sections of the carriageway, located at either end of the site. This enabled two de-icers to be compared under the same environmental conditions and levels of trafficking. The application of the de-icers was as follows:

Trial N° 1: Untreated and treated salt
Trial N° 2: Untreated and pre-wetted salt
Trial N° 3: Untreated and treated salt

The moisture content of the de-icers was approximately 3.3 per cent for Trial N° 1 and greater than 4.5 per cent for the other two trials.

Generally, the environmental conditions during spreading were similar for all of the trials, with the only variation a higher wind speed during Trial N° 2 in the direction from lane 2 to lane 1. The conditions were very similar for all the trials after spreading, with no rainfall and a maximum night time relative humidity of approximately 90 per cent. The volume of traffic was similar for the three trials, being equivalent to 20,000 and 40,000 vehicles with a wheelbase between 2m and 6.5m in lanes 1 and 2, respectively.

The wet wash method developed by TRL was used to collect salt from sets of three transverse strips within the trial site at different times during each trial. Each strip comprised eight 1m long x 1.2m wide panels that spanned the full width of the carriageway. Measurements were made of the distribution and quantity of salt discharged immediately after spreading. Residual salt levels were measured 12 hours, 24 hours and 48 hours after spreading. A weighbridge was used to determine the total amount of each de-icer discharged during each trial, and the average mix proportions of the pre-wetted salt.

It was originally intended to carry out only two trials, with each trial using separate spreaders for the untreated and treated/pre-wetted salt. However, the weighbridge measurements indicated that in the first trial the amount of untreated salt discharged was approximately twice the target amount and twice the amount of treated salt. For the purposes of comparing the untreated and treated salts, it was decided that a repeat trial was required (Trial N° 3) and that for all further trials the same spreader would be used for application of both treatments. The spreader was recalibrated for all three de-icers before Trial No 2. Furthermore, test runs were made by Staffordshire County Council in accordance with Appendix C of BS 1622 which confirmed that the amount of each de-icer discharged after calibration was within 5 per cent of the target.

Overall salt discharged and distribution

Other than the untreated salt in Trial N° 1, the total amount of salt collected from the three test strips during each trial was less than the target amount, ranging from 62 per cent to 99 per cent of the target figure. The majority of the salt was spread within lanes 1 and 2, ranging from 60 per cent to 94 per cent of the target spread rate averaged for both lanes. The target spread rate of salt for the pre-wetted salt was 15.6g/m2 (14g/m2 of dry salt and 1.6g/m2 of salt in the brine). The amount of salt spread to lanes 1 and 2 was:

- Pre-wetted salt : 94 per cent of the target in Trial N° 2 (this equates to 73 per cent of the untreated salt target for this trial)
- Treated salt : 73 and 60 per cent of the targets in Trial N° 1 and 3 respectively
- Untreated salt : 79 and 78 per cent of the targets in Trial N° 2 and 3 respectively

With the exception of the untreated salt in Trial N° 1, there was little wastage to the hard shoulder and verge; the amount of salt collected in the hard shoulder of lane 1 was less than one half of one per cent of the total collected and the amount collected in the hard shoulder of lane 2 was less than 6 per cent.

The peak of the salt distribution was generally in lane 2 with significantly more salt spread in lane 2 than lane 1. Generally, the peak tended to be nearer to the centre line for the untreated salt, although the wind may have been a contributory factor in Trial N° 2. The peak for the pre-wetted salt was furthest from the spreader. The amount of salt spread in lane 2 ranged from 87 to 162 per cent of the target amount for that lane. The amount of salt spread in lane 1 ranged from 25 to 70 per cent of the target amount for that lane, but the amount in the nearside of lane 1 was significantly less than in the offside. The amount of salt spread to approximately 25 per cent of the target width was less than 25 per cent of the target rate.

The amount of salt discharged that was suggested by the weighbridge measurements generally differed from that calculated from the salt collected from the test strips. The differences cannot be explained by errors in the salt collection measurements. There was also inconsistency in the weighbridge measurements from trial to trial, and in the way the weighbridge measurements varied from trial to trial when compared with the variation in the amount of salt collected. It was concluded, therefore, that the weighbridge measurements were subject to a random error of up to 50kg due to an unknown mechanism; if they were accurate they would indicate that the amount of salt discharged varied from 45 per cent above to 40 per cent below the target amount.

Because the amount of brine discharged during pre-wetted salting was not measured by the spreader, and because of the error in the weighbridge measurements, it cannot be confirmed that the mix proportions of the dry salt and brine components of the pre-wetted salt were those targeted. In Trial N° 2, the weighbridge measurements suggested that the mix proportions for the pre-wetted salt were 95 per cent dry salt: 5 per cent brine by weight. However, the test run made in accordance with Appendix C of BS 1622 after Trial No 2, when the effect of the error would have been less, the weighbridge measurements suggested that the mix proportions of the pre-wetted salt were 82 per cent dry salt: 18 per cent brine by weight. The peaks of the salt distributions for the untreated and pre-wetted salts in Trial N° 2 were in different positions across the carriageway, which cannot be explained fully by differences in the weather, and it is assumed that this was because the formulations of the two de-icers were different. The salt concentration of a sample of brine was found to be about 1 per cent, well below the target of 26 per cent.

Residual salt after trafficking
The most significant decrease in the residual salt level occurred during the first 12 hours after spreading, with a maximum loss in lanes 1 and 2 of 49 per cent of the salt before trafficking. The maximum percentage loss in lanes 1 and 2 was 54 per cent after 24 hours and 68 per cent after 48 hours.

Overall, similar losses were measured for each de-icer over the 48 hour duration of each trial. The pre-wetted salt showed the greatest percentage loss after 12, 24 and 48 hours. The percentage loss was greater for the untreated salt than for the treated salt over the first 12 hours, the loss was similar for both de-icers after 24 hours, and was slightly greater for treated salt after 48 hours.

There is therefore some evidence that the treated salt experienced lower loss in the first hours after spreading, but any difference relative to the other de-icers was not significant after 24 hours. The pre-wetted salt loss was greatest, possibly as a result of the higher proportion of the salt spread in lane 2 where the trafficking was greater. Considering each lane separately, there was greater variation observed between the percentage losses for the different salt types. There was significantly more salt spread in lane 2 than lane 1, which would have probably resulted in a net transfer of salt from lane 2 to lane 1 over time. The lower losses measured for the treated salt in lane 1 could indicate more re-distribution for the treated salt than for the untreated or pre-wetted salt. There was closer agreement between the losses measured in lane 2, where the spread rate was higher than lane 1 and the transfer of salt less significant.

The measured loss was dependent on the residual salt measurements before and after trafficking and how representative they were of the total length of the trial site. The effect of longitudinal variations in the salt distribution (i.e. snaking) created uncertainty in these measurements. Significant longitudinal variations in the salt distribution were evident before and, for some trials, after trafficking indicating that trafficking may not always lead to a more uniform distribution on negatively textured road surfaces. Overall, the differences in the salt losses measured for the different de-icers are considered to be insignificant when the longitudinal and transverse variations in the salt distribution are taken into account.

Comparisons with previous research
TRL has conducted a number of performance and road trials with untreated, pre-wetted and treated salt. During Phase 1 of the NSSRG research programme, a few performance trials were carried out on the same spreader when the de-icer used for the dry component for pre-wetted salting was the same as that used for dry salting. The amount of salt collected from the target area during pre-wetted salting was, on average, 7 per cent more than that due to the ratio of the salt contents discharged. In the Staffordshire trials, the amount of salt collected from the target area was, on average, 7 per cent less during pre-wetted salting than during dry salting, but this difference has been attributed to the higher amount of salt discharged during dry salting.

The first trials conducted by TRL with pre-wetted salt were in the late 1980s. The performance of dry salt wetted to a moisture content of 5 per cent and pre-wetted salt with mix proportions 70 per cent dry salt: 30 per cent brine by weight was compared. No significant differences in the residual salt levels were found. It is concluded that the findings from the performance trials in Phase 1 and the pre-wetted trials in the late 1980s are consistent with those from the Staffordshire trials. Note that in the Staffordshire trials, the moisture content of the dry salt was about 5 per cent.

In 2006, TRL carried out 11 trials on the M62 to compare the salt distribution of untreated and treated salt. On average, 13 per cent more treated salt than untreated salt was delivered to the target area, although these differences could have been the result of differences in the gate height, hence the amount of salt discharged. In nosebag tests, 11 per cent less treated salt than untreated salt was discharged when the gate was at the same height. Therefore, the findings from trials on the M62 and the Staffordshire trials are consistent.

The rate of salt loss due to trafficking in the Staffordshire trials on negatively textured surfacing was significantly less than that measured in pre-wetted salting trials on the A52 (Lincolnshire) and the A33 (Hampshire) on positively textured surfacing. The rate of salt loss was also lower in the Staffordshire trials than in other trials conducted by VTI (Swedish National Road and Transport Research).

Calibration of spreaders

The Staffordshire trials have demonstrated how important it is that spreaders are correctly calibrated. The amount of salt discharged in the calibration runs compared well with the target but it would appear that correct calibration at one set of settings (with a spread rate of 10g/m2 and spread width 6m) is no guarantee that the amount of salt discharged and the salt distribution will be acceptable at other settings (e.g. 20g/m2 and spread width 8m). Clearly, spreaders need to be calibrated for each de-icer at the target moisture content and for each setting at which they are to be used.

It is considered that the uncertainty regarding the mix proportions of the pre-wetted salt in these trials may well be repeated during many 'live' pre-wetted salting operations. Therefore, it is recommended that the mix proportions of pre-wetted salt are monitored during all pre-wetted salting by use of a flow meter or similar device to measure the amount of brine discharged. The total amount of brine can also be compared with the total weight of solid de-icer discharged.

Furthermore, it is recommended that the spread pattern is assessed visually on a regular basis so that poor distribution, as to lane 1 in these trials, can be detected at an early stage and be corrected. This is particularly important if spread rates are being reduced. The unevenness of the salt distribution in these trials demonstrates that spreaders should be calibrated for each de-icer they are to spread at the target moisture content. Most importantly, the results of these trials indicate that they should be calibrated for each setting at which they are to be used and frequent visual checks should be made of the spread pattern.

Main conclusions

- The amount of salt spread to lane 2 was close to the target amount, but lane 1 was under-salted such that the amount of salt spread to about 25 per cent of the target area was less than 25 per cent of the target spread rate. There was little wastage to the hard shoulders and verge.
- There were no significant differences in the salt distribution of each de-icer before trafficking, although there were small variations in the position of the peak of the distribution.

- In most trials, about 40 per cent of the salt spread was lost due to trafficking during the first 12 hours after spreading. The amount of salt remaining 48 hours after spreading ranged from 32 to 51 per cent of the amount spread.
- Whilst there were differences in the percentage losses with trafficking for the three de-icers, these were insignificant when the differences in the salt distributions and levels of trafficking in each lane are taken into account.
- The findings from these trials are consistent with those from previous trials carried out by TRL for the NSSRG and Highways Agency in which the salt distributions of untreated, treated and pre-wetted salt were compared.
- The salt loss due to trafficking in these trials on negatively textured surfacing was significantly less than that measured in other NSSRG pre-wetted salting trials on positively textured surfacing.
- The unevenness of the salt distribution in these trials confirms that spreaders should be calibrated for each de-icer they are to spread at the target moisture content. Most importantly, it is considered that they should be calibrated for each setting at which they are to be used and frequent visual checks should be made of the spread pattern.
- It is recommended that mix proportions should be monitored during all pre-wetted salting operations by use of a flow meter or similar device to measure the amount of brine discharged.

5 Dissolution rates of de-icers

The dissolution rate is an important factor in determining the length of time required for solid de-icers to become effective on road surfaces. Moisture can be absorbed by de-icers directly from the atmosphere, from the road surface or from liquid added at the time of spreading. The National Salt Spreading Research Group (NSSRG) therefore commissioned TRL to investigate the dissolution rates of different de-icer types applicable to UK de-icing operations. The objective was to investigate the effect of the different de-icer properties on the rate of dissolution under various climatic and surface conditions.

Trials were performed using 5 de-icer types:

- Untreated rock salt
- Rock salt treated with Safecote
- Rock salt treated with EcoThaw
- Pre-wetted rock salt
- Pre-wetted fine grade salt

The testing was performed on a dense asphalt surfacing at the TRL site and involved the spreading of samples of each de-icer and collection 1, 2, 3.5 and 5 hours after spreading. The remaining solid particles were collected separately at each collection, allowing the amount of salt in solution to be calculated.

In total 4 trials were carried out under differing levels of humidity, temperature and surface condition.

Overall dissolution rates

The majority of dissolution that occurred during the duration of the tests occurred in the first hour after spreading. It is considered that this is most likely a result of the rapid initial dissolution of the finer particles contained within the de-icers. It should be noted that these tests were undertaken with no trafficking of the salted surfaces and this would tend to break up the larger de-icer particles to increase their rate of dissolution. However, the finer particles would also tend to be dispersed and removed from the road surface by vehicle draughts, particularly in dry conditions.

Despite the de-icers being tested as supplied and their moisture contents being different, the average amount of the solid component of the salt in solution on a dry surface after 1 hour was 36 per cent for all of the tested de-icers. On a damp surface, the 1 hour average ranged from 42 to 49 per cent when the moisture content of all the de-icers was approximately 2 per cent.

Effect of de-icer type

The testing was carried out with samples of a representative particle size distribution. In the absence of trafficking, the differences in the measured dissolution rates between the different de-icer types did not appear to be significant in terms of their anti-icing capability. The particle size distribution (i.e. amount of fines) appeared to be the most important factor, irrespective of the de-icer type. It has been shown that the fines content reduces with an increase in the moisture content, and this will have implications for the salt distribution and the rate of dissolution across a carriageway.

Effect of climatic and surface conditions

As would be expected, a damp surface produced an increase in the amount of dissolution. The humidity level, whilst having some effect, was shown not to be particularly significant on a damp surface and temperature less so again. The results from one trial indicated that the humidity level is not significant when the surface is dry.

Implications for salt spreading

The results have indicated that the presence of finer particles on the road surface is important to allow rapid dissolution and an immediate anti-icing effect. However, the finer particles may be more subject to wind and vehicle draughts and therefore more easily displaced from the road surface over a period of time. Pre-wetting the salt, where the fines will be dissolved or held in suspension within the brine, or treating the salt to dissolve or bind the fines to the larger particles may therefore offer benefits through increased retention of de-icer on the road surface.

The increased retention of de-icer, fines in particular, is normally assumed when pre-wetting salt because pre-wetted salt with 7g of dry salt and 3g of brine is generally considered equivalent to 10g of dry salt, even though a proportion of the pre-wetting agent has no de-icing properties. Similar assumptions have been made by some authorities when reducing treated salt spread rates.

It has been shown that the particle size distribution may vary across the road surface with a higher proportion of larger grains towards the margins. Again, pre-wetting or treating the salt appears to offer some benefits through a more uniform distribution of the fines. Not unnaturally, the use of a more uniform salt grain size, such as with 3mm salt, also helps to produce a more uniform particle size distribution across the carriageway.

With respect to the conditions under which salt is spread, it would appear the most significant factor is the presence of moisture on the road surface. There is likely to be significant loss of fines over time due to trafficking when dry untreated rock salt with a low moisture content is spread when the road surface is dry. When the road surface is damp or wet the moisture present will facilitate dissolution of the finer particles and help retention on the road.

Main conclusions

1. In the absence of traffic, most dissolution that occurred during the five-hour trials occurred within the first hour after spreading. On average, for the five de-icers tested, 36 per cent of the solid component of the de-icers was in solution after 1 hour during one trial on a dry surface, and from 42 to 49 per cent was in solution after 1 hour during three trials on a damp surface.
2. The rate of dissolution from 1 to 5 hours was higher on a damp than on a dry surface. On average, for the five de-icers tested, 52 per cent of the solid component was in solution after 5 hours on a damp surface, and 37 per cent on a dry surface.
3. The trial results indicate that finer sized particles are important for rapid dissolution and an immediate anti-icing effect and that this is particularly important in the absence of trafficking to crush larger particles.
4. The longer term effectiveness of dry salt is likely to be seriously compromised on dry roads because many of the finer particles may be dispersed by wind and vehicle draughts before they enter solution and become effective.
5. Pre-wetted and treated salt appear to offer benefits over dry salt because of increased retention of the fines on the road surface over time without any significant difference being apparent in the initial dissolution rate. However, the effectiveness of all three de-icers is clearly dependent also on the spread rate which also affects the amount of chloride that remains on the road surface.
6. There were small differences in the rate of dissolution of the different de-icer types under the conditions tested which appeared to be dependent primarily on the dissolution of the finer particles.

7. The fines content of a de-icer reduces when its moisture content increases, with implications for the salt distribution and, hence, rate of dissolution across the carriageway. When the moisture content of dry untreated rock salt is 3.5 per cent rather than 1.5 per cent, the proportion of particles passing a 0.6mm sieve can be halved, i.e. 15 rather than 30 per cent.

8. A more uniform grading of salt could result in a more uniform rate of dissolution across a whole carriageway due to the smaller range of particle sizes. However, a reduction in the amount of fines present may lengthen the lead time after spreading before an application becomes fully effective.

6 Skid resistance of de-icers

Simulated trafficking using the Road Test Machine was used to wear three types of asphalt surfacing test slabs under controlled laboratory conditions and the effect of 7 salt de-icers on their wet skid resistance assessed at 1,000, 20,000 and 55,000 wheel passes using a British Pendulum Tester at 20°C.

There did not appear to be a significant difference in the wet skid resistance results obtained when using the 7 types of de-icers and the three types of asphalt assessed at the three stages in the simulated trafficking cycle. De-icer applied at an equivalent application rate of 40g/m , either as 10% or 20% concentration solutions (by weight) or as loose de-icer particles was found to have no significant effect on wet skid resistance measured using the pendulum.

Values of wet skid resistance after a minimum of 5 pendulum swings were found to be either equal to or within 1 or 2 units of the untreated wet skid resistance for the test surface being assessed. The application of particulate de-icer to wetted surfaces was found to affect some of the first and second swings of the pendulum testing, either giving values 1 to 5 units lower or higher than the value found after a minimum of 5 swings.

This represents a small modification in skid resistance and is to be expected, as the presence of virtually any kind of particulate material between the tyres of a vehicle and the road surface will tend to reduce skid resistance by some degree. It should be noted that this effect was not seen in all of the tests and it is considered likely that this effect would not be long lasting on road surfaces, as dissolution occurs relatively rapidly after most 'live' salting operations.

The application of particulate de-icer on the dry skid resistance of asphalt surfaces was found to have a significant effect. Values of dry skid resistance measured using the pendulum dropped by between 15 to 35% of the slabs untreated dry resistance after the first salt application. Continued application of salt caused further decreases in dry skid resistance to a maximum loss approaching 45% of the slabs' dry skid resistance after a maximum of 60 consecutive salt applications.

It should be noted that the test methodology included this number of salt applications in order to study the situation that occurs through to extreme amounts of salt being present on the surface. The amount of salt after 60 test applications was far more than would be present on a 'live' road during normal winter conditions. The resultant dry skid resistance of the slabs with this extreme amount of salt was approximately equivalent to the wet skid resistance of an untreated surface.

Continued pendulum testing after the cessation of salt application caused a recovery in dry skid resistance. It is considered that the reduction in dry skid resistance values observed during the tests when de-icing salt was applied in quantities that would normally be expected to occur on 'live' roads in winter, could potentially indicate that road users may, on occasion, misunderstand the level of skidding resistance available to them from apparently dry, salted road surfaces.

This is of some potential concern and supports the widely accepted view that salt should only be applied to road surfaces when there is a significant risk that the road surface could become adversely affected by ice and/or snow. However, dry skid resistance levels are generally high and these tests indicate that the maximum potential decrease in skid resistance arising from applying salt to a dry road would appear to be no more than that which would occur if the road surface simply became wet, even when the amount of salt present is unrealistically high.

The tests indicate that, once a salt application on the road surface has gone into solution and then re-dried through evaporation, skid resistance is restored to values close to those for untreated dry surfaces. Due to the fact that the skid resistance of an icy road is typically very much lower than that of a wet road, a wet salted road, or a dry salted road, it is considered that the use of de-icing salt remains an extremely effective road safety benefit when applied at appropriate times and in appropriate quantities.

7 Review of salting trials

The National Salt Spreading Research Group (NSSRG) commissioned TRL Ltd in 2001 to undertake a programme of research into the performance of highway winter maintenance salt spreading equipment. The first phase of the programme mainly focussed on spreader performance under controlled conditions on the TRL research track in Berkshire, and was completed and reported in 2005. This phase included thirteen track based trials and five road trials being undertaken with the assistance and co-operation of members of the NSSRG, as well as Strategic Highway Research Program (SHRP) tests to determine the de-icing capabilities of eight de-icers. A 'Best Practice' guidance document for spreading salt was produced for the benefit of all NSSRG members.

Phase 2 of the programme was commissioned following the Phase 1 final report and has so far included the undertaking of a further two track trials and four road trials of spreading equipment, as well as investigations into the dissolution rates of five de-icers, the investigation into practices of winter maintenance of footways and cycleways across the country and laboratory trials of the effects of salt application on the skidding resistance of road surfaces.

Before and during the period of the NSSRG research programme, the Highways Agency separately commissioned TRL to carry out certain performance trials of winter maintenance techniques, equipment and materials, and kindly made some of the results of those trials available to the NSSRG.

It is clear from the above that a considerable amount of work has now been undertaken in this area, and that this has involved a significant level of financial investment by the highway authorities and practitioners comprising the NSSRG, as well as investment by way of time and equipment from other NSSRG members. As Phase 2 of the research programme is currently nearing completion, it is appropriate to undertake a review of the trials undertaken to date in order to draw together the overall findings of the work, to assist in determining the value of the NSSRG research to stakeholders, and to ensure that any lessons arising from the work can be learnt and incorporated into future trial methodologies. This 'Review Report' was therefore commissioned by the NSSRG in September 2007.

The overall aims of the NSSRG research programme include assisting highway authorities and practitioners with operational decisions concerning the choice, setup and performance of their winter maintenance salt spreading equipment. The main drivers behind the work include improving the cost effectiveness of UK highway winter maintenance operations and a desire to ameliorate the environmental impact of those operations by reducing the amount of salt spread on the roads without compromising safety.

Specific objectives of the NSSRG Phase 1 and 2 trial programme include:

- Researching spread rate and distribution patterns of dry (untreated) salt, pre-wetted salt and salt treated with agricultural based additives (treated salt), as well as brine only application, through dynamic performance testing.
- Determination and confirmation of whether specific distribution systems are capable of delivering the required performance standards, in terms of required coverage and rate of spread for different de-icers.
- The development and evaluation of techniques for the measurement of residual salt levels.
- Comparisons of the performance of different de-icer types in highway based field trials.

- o Identifying optimum salt grade, purity and moisture content for dry and pre-wetted salt applications.
- o Identifying optimum rates of spread for different salting techniques.

The trial programme to date has tested the spread rate and distribution patterns for a wide range of equipment types and materials in both track based and road based trials, and techniques for the measurement of residual salt levels and other test methods have been evaluated and developed. The objectives of the trials have focussed on assisting authorities in understanding the performance of equipment and materials in the configurations and specifications as are either actually employed in 'live' salting operations or would potentially be employed in future 'live' operations. The variations in measured performance of the equipment and materials during the trials have been relatively large, and this may relate to the various equipment configurations and settings currently used by highway authorities, as well as to a number of other influencing variables that altered between the trials. This is considered to be an important finding but it has also reduced the potential for the trials to provide robust comparisons regarding the performance of different de-icers and equipment types, and the programme has therefore not yet resulted in the provision of advice regarding optimum salt grades and spread rates for different materials and equipment combinations.

The research to date has however successfully produced valuable results in the specific objective areas, as well as in other closely allied areas. These include the production of detailed performance reports for a considerable number of specific equipment and de-icer combinations, with the performance trials highlighting that:

1. As currently configured and operated by highway authorities, salt spreading equipment may be delivering less than the targeted salt spread rates within traffic lanes (trials have consistently demonstrated this effect).
2. As currently configured and operated by highway authorities, salt spreading equipment may be producing relatively inconsistent performance (repeat tests under similar environmental conditions have produced variations of up to 30 per cent of the target spread rate in the amount of salt collected from traffic lanes).
3. Current salt spreading equipment generates longitudinal and transverse variation in spread and these 'snaking effects' are of a similar magnitude whether dry, treated or pre-wetted salt is used.
4. Variations in the performance of different spreading equipment as currently configured and operated by highway authorities appear to be greater than variations resulting from the use of different available techniques and materials. For example, it is considered likely that current variations in the performance of the equipment configurations being operated by authorities across the country are larger than the variation in performance that an authority would achieve by changing from untreated to treated salt, or from dry salting to pre-wetted salting etc.
5. Before purchase, highway authorities should request that manufacturers demonstrate their equipment is capable of achieving the required distribution specification for the relevant de-icing material, technique and road network. The most appropriate settings to achieve the specification should be provided by manufacturers and carefully noted and utilised by authorities.
6. Salt spreading equipment requires settings to be specifically adjusted for the particular de-icer type, grading and moisture content being used. There is also evidence to suggest that performance checks are required for each specific spread rate and spread pattern being used.
7. Variations in stockpile moisture content will affect spreader performance. De-icing materials should therefore be stored in a controlled manner to minimise such variations and authorities should regularly check the moisture content of each

stockpile. Where appropriate, equipment settings should be adjusted to account for the measured moisture content.

8. Relevant highway authority personnel such as salting vehicle drivers should be knowledgeable and receive specific training in the capability, performance, set-up and calibration of the spreading equipment systems they utilise. This is in addition to the standard NVQ requirements. Training may be most appropriately delivered by the equipment manufacturers.
9. Highway authorities should exercise caution when considering the reduction of salt spread rates to less than 10 g/m² and, before instigating such a reduction, should satisfy themselves that the spreading equipment and set-up they employ are delivering consistent and accurate spread patterns to the whole of the target area.
10. There is evidence that trafficking does not redistribute de-icing materials sufficiently to eliminate initial 'snaking effects', an important factor when considering the reduction of spread rates.
11. Residual salt levels reduce markedly during the initial 12 hours after distribution regardless of whether dry, treated or pre-wetted salting techniques are employed. Trial results indicate that as much as approximately one half of the initial material can be lost during this period on a heavily trafficked road during dry road conditions.
12. There is some evidence to suggest that salt loss due to trafficking during dry road conditions is reduced on negatively textured road surfaces, compared to that for positively textured road surfaces.
13. Whenever liquids are employed for de-icing purposes, distribution systems should be equipped with flow meters so that the rate of spread of the liquid onto the road can be monitored and checked during and after the operation. This is in addition to ensuring that the concentration of the liquid solution is correct prior to the commencement of the operation.

One of the main challenges when undertaking research in the winter maintenance field is the large number of parameters that affect the performance of de-icers, and the trials undertaken to date have highlighted the need for these variables to be controlled whenever possible, and recorded and monitored when this is not possible. The difficulty in controlling 'real world' variables leads to a need to take particular care when interpreting the results of individual trials and applying these to wider scenarios. The practicalities of planning and undertaking both road and track trials to take place within limited weather windows cannot be overstated.

Some of the individual NSSRG performance trials have involved different grades of salt, different spread widths and different spreader types for each de-icer. Trials of different spreaders have involved different de-icer types, grades, spread widths and moisture contents. Direct comparison between the results of different trials across and outwith the NSSRG research programme is only appropriate once all the influencing parameters have been properly accounted for. Therefore, it is recommended that highway authorities carefully consider the research supporting claims made regarding new techniques, equipment and materials and satisfy themselves that apparently positive results from the research are directly attributable to that product.

It is notable that the trials to date have tended to utilise different de-icing materials in specifications as generally employed by highway authorities in 'live' operations. This approach allows general comparisons to be made between the performance of the materials in those specifications. However, because these specifications often include a number of differences between the materials being tested, the effects of changing a single parameter such as grain size or whether the material has been pre-wetted or not is difficult to determine from the results of such trials. Therefore, it may be that future trials should include studying the performance differences that arise from changing individual parameters. Also, the trials to date have been designed to investigate only a limited number of parameters. Investigation of, for example, the specific effects of moisture content and grading of de-icer on distribution and residual salt levels, would require trials designed specifically for this purpose. In order to provide unbiased comparisons, the spreading equipment utilised in any such trial would require separate calibrations so that the distribution is optimised for each de-icer.

Improvements and developments in trial methodology have been notable features of the NSSRG research programme and, as is usual in applied research, some of the lessons in this regard have been relatively hard won. One important conclusion that can be drawn from the trials to date is that each future trial should be carefully designed around a single set of achievable objectives. Although it is sensible to take maximum advantage of trials and research that have been designed around the aims and objectives of an individual sponsoring authority, care must be taken so that the scope of the trial is not broadened to the extent that interpretation and application of the results is jeopardised.

In general terms, the NSSRG trial programme to date has been designed so that the spreading equipment has been tested in the set-up configuration that would normally be used by the highway authority operating the equipment. This would appear to constitute a logical approach when the trial is investigating the current performance of the equipment when being used in a 'live' situation. However, this approach may not determine the maximum potential of the equipment if, for example, the set-up configuration used by the authority does not represent that which is most appropriate for a particular technique, material or spread rate as recommended by the equipment manufacturer. It has been established that in a relatively large proportion of the trials, the spreading equipment may not have been optimally set up for the specific de-icer and/or spread rate/pattern being tested. It is considered that issues such as those experienced during the trials with calibration, incorrect equipment settings, de-icer condition and possible equipment malfunctioning may well therefore not be limited to these trials but that they may also be experienced during 'live' salting operations albeit that these may not be routinely identified.

Therefore, another lesson to be drawn from the trials to date is the importance of obtaining precise details regarding the calibration procedure and specific set-up configuration for the equipment being trialled. This would be in addition to undertaking checks on spreader performance through static discharge tests and, where possible, weighbridge measurements. Knowledge of this information would greatly assist in the provision of advice to NSSRG members regarding optimum equipment settings for individual de-icing materials and distribution patterns.

In addition to the overall findings discussed above, this review of the NSSRG trial programme to date has resulted in a number of specific recommendations being made regarding future trial methodologies, such that:

- A suitably qualified and experienced person should be present at each trial with specific responsibility for ensuring that the trial equipment is satisfactorily calibrated and configured and that de-icing materials are of the appropriate quality and composition.
- Whenever practicable, manufacturers of the trialled spreading equipment should be present at each trial. They should, at least, be specifically invited to attend each trial.
- The NSSRG trial checklist should be employed during all trials.
- Spreading equipment should be calibrated and appropriately configured for the specific de-icer being trialled and for each spread rate and spread width.
- Spreading equipment should be calibrated as close to the commencement of the trial as practicality allows with the de-icing material that is to be used in the trial.
- Spreading equipment performance and de-icer condition should be checked immediately prior to each trial.

- Spreading vehicles should be driven and operated by suitably experienced and qualified operators.
- The spread distribution should be checked visually during a pre-trial test run.
- Where practicable, static discharge tests should be performed on each day of a trial and reliable weighbridge measurements should be made during the trial to confirm that the spreading equipment is operating within acceptable limits. This process should include direct measurements of brine concentration and discharge during trials involving pure brine solutions and/or pre-wetted salting.
- All available information regarding the configuration of the spreading equipment during the trials should be recorded.
- Where possible, data from on-board monitoring equipment should be collected to assist in confirming the configuration and performance of spreading equipment.
- A detailed check list should be used to ensure all actions have been carried out for each trial.
- During performance trials, the area of surface from which results are taken should be the full target spread width, margin and verge, with the trial panels marked out accordingly.

Highway winter maintenance is a direct, safety related service that is generally viewed by the UK public as being of particular importance to their everyday activities. The service is now directly incorporated into legislation across Great Britain in a way which reflects this importance but which also provides the potential for highway authorities to face litigation when accidents arise on roads adversely affected by winter conditions. Changes in the way in which Police investigations of road traffic accidents are conducted and the introduction of Corporate Manslaughter legislation later this year are also bringing highway maintenance and other road services into sharp focus. When these factors are coupled with the costs of carrying out highway winter maintenance operations, the purchase price of equipment and materials, the potential detrimental environmental side-effects of the over-use of de-icing materials and the variable nature of the UK weather and climate, it can be seen that properly managed independent research into the efficacy of highway winter maintenance operations and the performance of de-icer application systems, techniques and materials is of particular importance to the nation as a whole. Specific individual organisations undertake their own programmes of research in this field. However, the NSSRG holds a unique position in comprising member authorities from across the whole of the country, as well as representatives from a wide cross-section of manufacturers and suppliers. The NSSRG research programme is therefore considered to be of particular importance to highway winter maintenance activities across the UK and its findings are already proving extremely valuable in shaping the future of this highly important field.

Recommendations for the future direction of the NSSRG research programme that have arisen from this review report include building upon the work undertaken to date, reasserting the emphasis of providing practical guidance, using the existing knowledge and expertise of NSSRG members to best advantage, maximising the potential for specific issue ‘quick wins’ and addressing the all important issues of safe salting.

8 Salting trials on the M62 at Goole

A series of distribution only salt spreading road trials was carried out on the M62 near Goole, on a section of three-lane motorway road with hard shoulder at Junction 37. The trials were carried out with a Foden 4000 Series Snowplough Spreader. The spreader travelled along lane 2 of the westbound carriageway at approximately 60km/h and was set up to spread across all three lanes of carriageway from this position.

Two de-icers were used, 6.3mm Thawrox (untreated salt) and 6.3mm Thawrox Plus (Safecote treated salt) from the West Cowick and South Cave depots respectively. Their performance was assessed with respect to the following parameters:

- Achieving the Target Spread Rates
- Targeting the main zones accurately
- Transverse and longitudinal snaking effects of the spreader

Summary

For both types of de-icer, trials were conducted with Target Spread Rates of 10g/m2, with the hopper full, and 20g/m2 with the hopper filled to 10% and 100% of the maximum capacity. In addition, trials were conducted using the treated salt with a spread rate of 15g/m2 and hopper loads of 10% and 100%.

Each trial took place over the course of one night (with the exception of Trial N°9 and Trial N°10 which were carried out on the same night) and followed the same procedure. The spreader was loaded up at the depot and the on-board computer system set for the required Target Spread Rate, i.e. 10g/m², 20g/m², etc.

Prior to the commencement of each trial run, the hopper load was determined using the weighbridge at the depot. As the vehicle had an unladen weight of 10800kg, this weight was subtracted from that recorded on the weighbridge to give the quantity of salt within the hopper.

The trial site was closed to traffic and, prior to spreading of the salt, a road sweeper was used to wash and sweep the road surface. For Trial N° 1, background measurements were taken from each lane (including the hard shoulder) near the start and end of the trial site to determine the level of residual salt present. For Trial N°2 to Trial N°11, the entire site was wet washed to remove any residual salt present.

Collection of the salt was made from 4 strips, marked out along the length of the trial site at spacings of 100m, 160m, 250m and 370m relative to a starting reference point. Each strip comprised 11 adjacent panels, of dimension 1m long x 1.2 m wide, with two in the hard shoulder and three in each lane. Each lane was 3.6m wide and the width of the hard shoulder was 3.6m. The same panel locations were used for collection during each of the trials.

Immediately after spreading, the salt was collected from each of the panels by vacuuming using the wet wash method. The salt solution samples were then analysed to determine the salt content and therefore the salt distribution across and along the carriageway.

Conclusions

When treated salt was used the Measured Spread Rate, calculated from the total salt collected in Lanes 1 to 3, varied from 92% to 128% of the target. For the untreated salt, this rate ranged from 81% to 122% of the target.

At a spread rate of 20g/m², on average, the Measured Spread Rate in Lanes 1 to 3 was 115% of the Target Spread Rate for the treated salt and 102% of the Target for the untreated salt. However, a calibration trial of the test methodology indicated that the

Measured Spread Rates in the road trials may be overestimated by about 5% for the treated salt and underestimated by about 1.5% for the untreated salt. If this is taken into account, it is estimated that about 6.5% more treated salt than untreated salt was spread to Lanes 1 to 3.

During "nosebag" discharge tests at 20g/m², 11% less treated salt was discharged than untreated salt when the hopper was 10% full, whilst when 100% full, 6.5% less treated salt was discharged.

There was good salt coverage over the entire carriageway including the hard shoulder for both the treated and untreated salts.

The distribution across the carriageway was similar for both the untreated and treated salts. There was generally less variation across Lanes 1 to 3 for the treated salt spread at 15g/m² and the untreated salt spread at 20g/m² than for the treated salt spread at 10g/m² and at 20g/m².

There were some variations which are indicative of snaking along the length of the carriageway, but these were less when the hopper was 10% full and generally when treated salt was used. The hopper load (100% or 10%) appeared to have little effect on the Measured Spread Rate in Lanes 1 to 3 when treated salt was used. The salt discharged from the hopper was similar during the trials when the spreader settings were identical. However, the weight of salt discharged did not correlate well with the amount of salt collected (the Measured Spread Rates) and it is believed that the spread rates calculated from the weights are in error. The Predicted Spread Rates calculated from the post trial "nosebag" discharge tests compared reasonably well with the Measured Spread Rates.

9 Summary

The research carried out in Phase 2 represents a valuable body of work and, in conjunction with the work carried out in Phase 1 and on behalf of the Highways Agency, will provide the basis for Phase 3 of the research programme. During Phase 3, the NSSRG will expand its remit to cover all aspects of winter service for carriageways, footways and cycle facilities in the UK. This expansion in the aims has also been reflected in the renaming of the group, as the 'National Winter Service Research Group' (NWSRG).

10 Acknowledgements

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