Salt – an Essential Component of Winter Road Maintenance

A Report gathering recent research and innovation on Winter Service with Salt

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Contents

SCOPE

The scope of this study involved a search to assemble information about recent research and innovation on winter service with salt. The review included published information on de-icers and technologies. The following topics were covered:

- Socio-economic value of winter service
- Salt consumption in times of climate change
- Environmental impacts of de-icing with salt
- De-icing with salt and its role in a green transition and sustainability agenda
- Information and comparison between de-icing with salt and alternatives
- Innovation, especially in terms of optimization of spreading salt

EXECUTIVE SUMMARY

Sodium chloride (salt) is the most commonly used chemical de-icer in Europe. It is suitable for the majority of winter conditions, is relatively low cost and readily available. Life cycle assessment studies also show it to be the best tool environmentally.

Timely and efficient winter road maintenance makes a significant contribution to reducing serious personal injuries resulting from traffic accidents caused by slippery conditions. In addition to preventing traffic accidents, winter service with salt also prevents traffic jams on roads - shortening travel times, saving fuel and reducing traffic-related CO_2 emissions.

The increasing use of road weather information systems, IT, modern salt spreaders, and the widespread use of pre-wetted salt technology have contributed to minimising the number of traffic accidents in winter.

In the decades to come, as climate change brings milder winters and the use of advanced technologies evolves, winter service provision will become more accurate, efficient, cost effective and environmentally substantiable. It will also continue to play a crucial role in maintaining mobility and keeping roads and citizens safe.

Europe's winters are getting warmer

Europe now generally experiences fewer ice and frost days than in the past. Weather service forecasts suggest this trend will continue although there will be regional variations as to the amount and type of rain and snow precipitation during winter. While differences exist from region to region, long-term forecasts predict the disappearance of cold winters for individual regions.

De-icing salt consumption will continue to vary from year to year depending on the severity of the winter. Publicly available statistics currently show no clear change in salt consumption due to climate change and no general trend towards less salt consumption. Some increases in salt consumption may be explained by changing service levels.

Climate change is expected to bring warmer winters and more precipitation, which is expected to fall as rain rather than snow. It is nevertheless imperative that sufficient snow clearing equipment and salt stocks continue to be available for heavy snowfalls.

There is a drive for environmental sustainability in winter service provision

The decarbonisation of winter services is focused on:

- Salt production,
- Transporting salt from the production site to winter service silos and warehouses,
- Salt spreading (direct emissions and emissions from fuel production), and
- Electricity consumption in the winter service depot.

Spreading salt - the core process of winter service is the most energy consuming,and associated with the largest CO_2 emissions of all service processes. This is followed by the transport of salt from production sites to the winter service warehouses. The production of de-icing salt is of little importance in terms of energy consumption and CO_2 emissions.

Several options for decarbonising salt production have already been implemented or announced including: Use of electricity from renewable sources for the vehicles and machines underground as well as mine ventilation; Converting vehicles used for solar salt harvesting to drive with batteries or fuel cells; Running evaporated salt plants on electricity from renewable sources or steam from power-to-heat systems, in addition to electricity and steam from waste incineration plants.

Life cycle assessments of non-chloride de-icers provide a clear picture of the environmental impact categories in comparison with sodium chloride which is responsible for by far the lowest carbon emissions and has the lowest primary energy requirements.

Rail and ship transport should be preferred over trucks for the transport of salt to winter service depots - if appropriate logistics routes exist, and economic efficiency is guaranteed. In the future, trucks with battery and fuel cell drives will also be available.

In sensitive waters, the migration of runoff chloride is an issue and must be limited by specific measures such as modified winter service plans and regular adjustments and calibrations of the salt spreaders.

The new EU air quality regulation is intended to contribute to the bloc’s goal of zero pollutants by 2050. Contributions to exceedances of fine particulate matter (PM 10) limits resulting from winter salting of roads should be allowed to be deducted when assessing compliance with air quality limits, provided appropriate measures are taken to reduce concentrations.

Many industrial processes, such as those in the food industry, use brine (sodium chloride solution), which then must be disposed of as salt wastewater by discharging it into natural bodies of water or otherwise. To increase ecological sustainability, such dissolved salt can, after suitable treatment, be used for winter service, thus saving salt overall.

Focus on environmental issues in recent years has led to the emergence of a number of new ideas, as well as already developed and ready-made processes, that can produce salt from waste products. This so-called "circular salt" uses waste products that would otherwise be landfilled or backfilled in mines and replaces virgin products that are often transported long distances.

Alternative de-icers to salt are used, but often come with disadvantages

While salt is the most commonly used, other chloride-based de-icers - liquid calcium chloride and magnesium chloride - are used as alternatives to sodium chloride solution in wet salt technology. However, in direct liquid applications with these solutions there is a risk that chemical slipperiness can arise due to the formation of hexahydrates on the road, which significantly reduces road grip. Calcium chloride and magnesium chloride have the disadvantage of a double input of chloride into the environment compared to sodium chloride, and Calcium chloride is also classified as a hazardous substance. In addition, the costs of these chlorides, in both solid form and solution, are significantly higher than for sodium chloride, while their availability is far lower than that of sodium chloride.

Solid calcium chloride, usually mixed with sodium chloride, can be effective in combating slipperiness on roads with temperatures lower than -15 °C.

Non-chloride de-icers for roads include acetates and formates. Although these organic salts are biodegradable in water and soil, this involves consumption of oxygen. The melting process with these alternative de-icers is slower than with salt and the corrosive effect on galvanized steel must also be considered. The cost of these products is at least 10 times higher than salt.

In Europe, there are few known uses for chloride-free de-icing agents outside of airports. The chemicals used are potassium formate and potassium acetate. They are typically only used in sensitive, limited urban areas and not on a large scale like sodium chloride.

In one case, potassium carbonate is used in exceptional cases in pedestrian zones with natural stone floors or concrete slabs sensitive to de-icing salt, as well as in parks.

Winter service provision is evolving across Europe

The most significant innovation in winter service over the last two decades has been the direct application of brine onto roads, which is particularly suitable for preventive control of slippery surfaces. It improves winter service and leads to savings in salt, which reduce the impact on the environment and winter service costs.

The importance of direct brine application is now recognised in European countries where winter service is necessary, and projects have been initiated to implement this technology in winter service units. This is already partially complete, but further investments in brine production systems and suitable spreading machines are required.

In addition to the liquid-only spreading machines, hybrid machines have proven particularly advantageous. Depending on the road conditions and weather forecast these machines can apply both pre-wetted salt and brine. Practical experience shows that direct brine application makes it possible to increase the amount of brine used in a mild winter period to more than 100 percent of the amount of solid salt still required. A modern winter service today has technical equipment that allows it to spread either pre-wetted salt or brine, depending on the weather and road conditions.

It is increasingly recognised that brine spreading on cycle paths is much more suitable than the use of abrasives. With brine applied preventively, cycle paths can usually be used even in winter. On ice days the brine distribution can reach its limits; then the slipperiness is combated with pre-wetted salt.

Other recent innovations for winter service include:

- Snowploughs with a brine injection system,
- use of a tire sensor, that automatically detects the road surface conditions,
- spreading machines with integrated real-time road weather data, and
- use of floating car friction data.

Technology is enhancing the efficiency and cost-effectiveness of winter service programmes

IT and technology are already playing a crucial role in driving efficiency and effectiveness in winter service provision around the world. Ongoing research and innovation will ensure that winter service becomes increasingly tailored and sophisticated.

The current development of an IoT system combining geoinformation, weather data and sensor measurements with digital support is particularly promising. It should make winter service more precise while also reducing the number of necessary gritting trips and salt consumption.

Clear Roads - the National Research Consortium for winter highway maintenance in the USA - is currently developing a tool for quantifying the benefits of snow-and-ice operations and the costs associated with those benefits to illustrate the substantial economic and ecological gains of investing in snow-fighting equipment, road treatment programmes and technologies such as road weather information systems. Its output will be used to inform management about the real-world costs, benefits and value of a sufficiently funded snow-and-ice-control programme that could guide transportation agencies in determining an appropriate annual budget for these programmes. The study is expected to provide a tool with a list of data inputs and methodology as well as a tool guide and results will be available this year.

1. INTRODUCTION

This report explores the latest developments in Winter Service around the world – from the of new approaches, technologies and systems available through to the impact of climate change. It identifies optimal solutions in delivering an efficient, cost-effective winter service that benefits both citizens and the economy.

Winter service is a complex and dynamic system: the weather, climate, technologies, traffic, and road areas are all subject to changes that must be considered during work.

Those responsible for winter service are required to adapt their service to the current road and weather conditions. Particular attention is paid to salt consumption and the impact of winter service on the environment.

Science, industry, and users work constantly to further perfect winter service. There is an intensive exchange of knowledge at national and international congresses and exhibitions which is complemented by European standardisation of the equipment and materials required for winter service.

2. SOCIO-ECONOMIC VALUE OF WINTER SERVICE

- Winter service prevents both road accidents, and the injuries and deaths associated with them.
- Investment in winter service equipment and technologies brings both economic and social benefits
- New tools and technologies provide authorities with an accurate cost/benefit analysis

Transportation agencies are responsible for combating the adverse effects of inclement weather. These efforts require strategic economic planning to ensure the agency receives an adequate budget to meet expectations and that they get the most out of the available budget and resources. The economic benefits of a fully funded snow-and-ice programme, as well as the costs of failing to maintain it, may not be apparent to those responsible for budget allocations.

In 2024, Clear Roads - the National Research Consortium for winter highway maintenance in the USA - began developing a tool for quantifying the benefits of snow-and-ice operations and the costs associated with those benefits, in order to illustrate the substantial economic and ecological gains of investing in snow-fighting equipment, road treatment programmes and technologies such as road weather information systems. The output of this tool will be used to inform management as to the real-world costs, benefits and value of a sufficiently funded snow-and-ice-control programme. It will serve to guide transportation agencies in determining an appropriate annual budget for these programmes. The study is expected to provide a tool with a list of data inputs and methodology as well as a tool guide. Results will be available this year [1].

Another Clear Road project produced a step-by-step guide and flowchart tool to help agencies identify or develop severity index methods to fit their needs and available data sources. As estimating the impact of weather on roadway maintenance resources is becoming an increasingly important issue for road maintenance agencies, a recently completed complementary project produced training modules geared toward three key audiences: division directors, snow and ice managers, and supervisors. They incorporate audiovisual materials, discussion topics, and interactive exercises and will help practitioners design and develop indexes to suit their agency's particular needs [2].

Extrapolated for all country roads in Germany, and taking current mileage into account, winter road maintenance with de-icing salt can be seen to prevent around 7,500 accidents with personal injuries within the first few hours of its use - including around 2,200 serious accidents with injuries or deaths. These figures make it clear that in winter conditions not only do the number of minor accidents increase, but serious personal injuries also increase above average. Timely and efficient winter service makes a decisive contribution to reducing these serious personal injuries. In particular, winter services with the increasing use of road weather information systems, the use of modern salt spreaders and the widespread use of pre-wetted salt technology, contribute to minimising traffic accidents in winter (Figure 1) [3, 4].

The savings related to Germany within a winter period through de-icing salt in the first hour after application are extrapolated [5]:

- 800 million euros on out-of-town roads
- 200 million euros on motorways
- 1,300 years of travel time
- 16.5 million litres of fuel
- 40,000 t CO_2 (corresponds to around 0.2% of all traffic emissions)

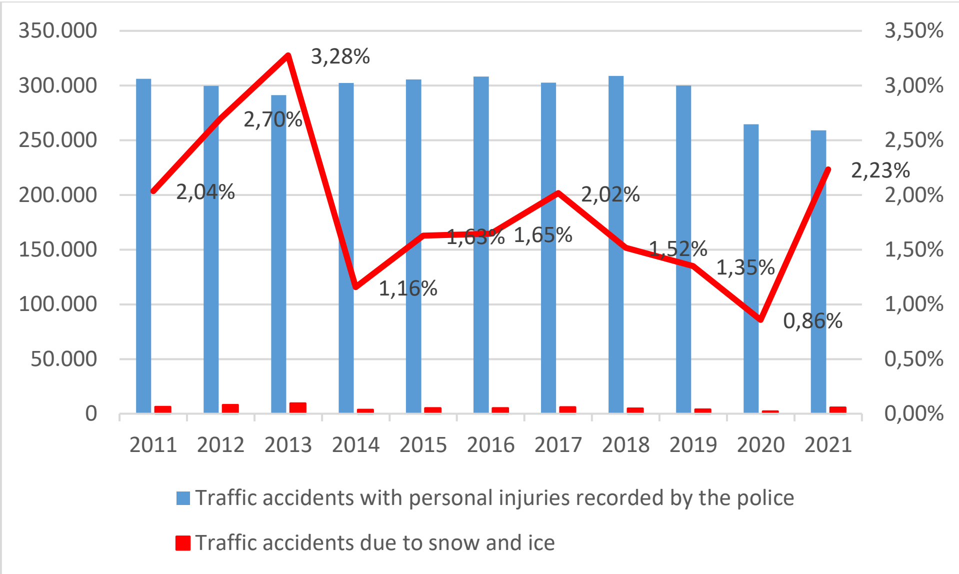


Figure 1: Weather-related traffic accidents in Germany

3. SALT CONSUMPTION IN TIMES OF CLIMATE CHANGE

- Climate change will influence winter service in the longer term with warmer winters likely to lead to fewer snow and ice days and more precipitation falling as rain
- While there are generally fewer ice and frost days than in the past, salt consumption has held steady and even risen due to a broadening of winter service provision
- Comparing the winter service provision in different countries and regions is not exact as there are many variables – length of roads served, types of roads, levels of service

- Changes in both climate and mobility behaviour will mean adjustments to winter service, but provision for bad weather periods must remain - including adequate storage of de-icing products and availability of machines for when they are needed.

Demand for salt in individual countries during winter depends on: the type, extent and development of the road network and other areas in need of winter service; the traffic; user demand; the strategy for winter service; and the winter weather. In the long term, demand will also be influenced by climate change.

Generally, more salt is used during a colder winter with a lot of snowfall. However, temperatures and snowfall vary across Europe and within countries. A winter is seldom mild/severe across the whole country and an average temperature for the whole country does not present a true picture of how the winter has been because countries are salted differently depending on standards and the number of roads. For example, a winter with little traffic and a lot of precipitation is salted much more than a winter where it is cold for a long period but there is no precipitation and so no salting.

In general, there are now fewer ice and frost days than in previous years. But salt usage varies year on year as in the past, depending on the severity of the winter. There is currently no clear trend towards more or less salt consumption due to climate change. A partial increase trend in salt consumption can be explained by changing service levels.

There are no official European statistics on the consumption of de-icing salt and annual consumption quantities are only given for some countries or for specific road types. The following examples from European countries show the high volatility and trends in salt demand:

<u>Austria</u>

Salt consumption reached maximum values on the Austrian motorways in the years 2008-2011, 2017-2019, and 2021 (Figure 2) [6] as a result of heavy snowfall and long winter periods. In 2023 there was another increase in salt consumption. December stands out as a particularly high-consumption month and it is noted that the proportion of brine spreading is increasing.

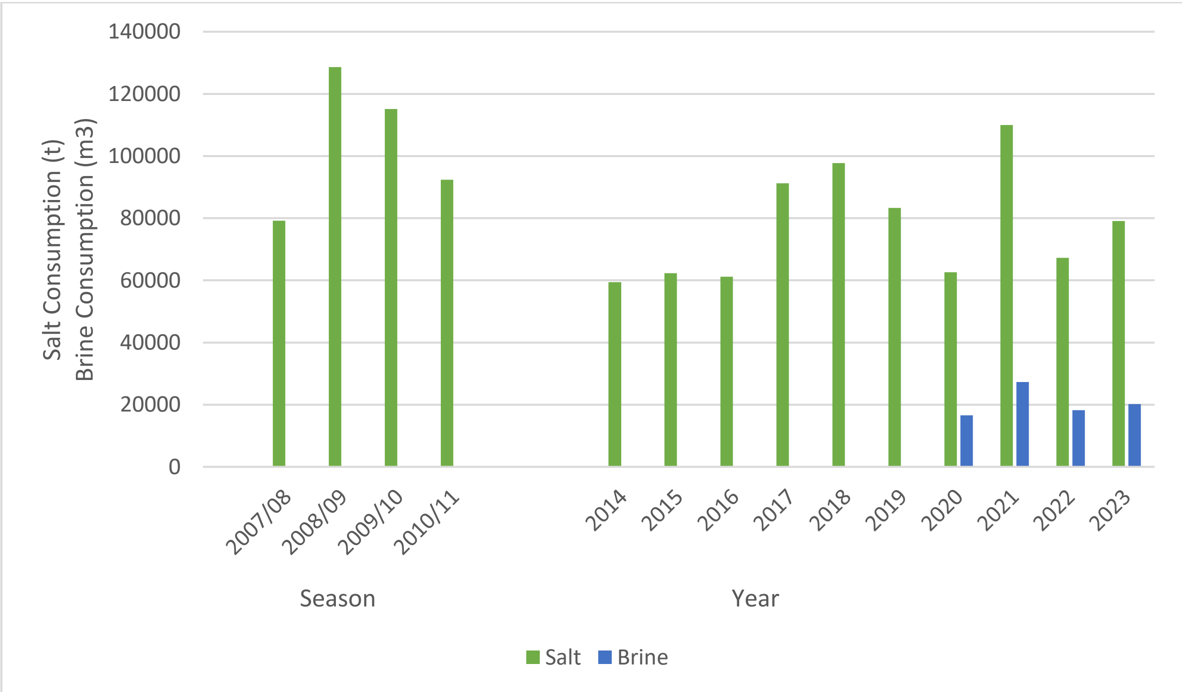


Figure 2: Salt usage on Austrian highways (Source: ASFINAG)

Germany

Figure 3 shows the specific consumption of dry salt for spreading and brine production at winter service facilities for winter road maintenance on national motorways ("Autobahnen"), except privately operated motorways, and federal highways ("Bundesstraßen"). The highest specific consumption occurs on the motorways. There has been no clear consumption trend over time. Motorways have either four or six lanes, while highways usually have only two lanes. This leads to different salt requirement per kilometre. In winter 2023/2024, total consumption for motorways was 293.000 t and for federal highways 268.000 t. Additionally, brines (NaCl, $CaCl_2$, $MgCl_2$) are purchased. Salt consumption on national motorways was not reported in the winters of 2020/2021 to 2022/2023 as a result of the establishment of the Autobahn GmbH,. For the winters of 1998/1999 and 1999/2000, consumption data for both road types are missing.

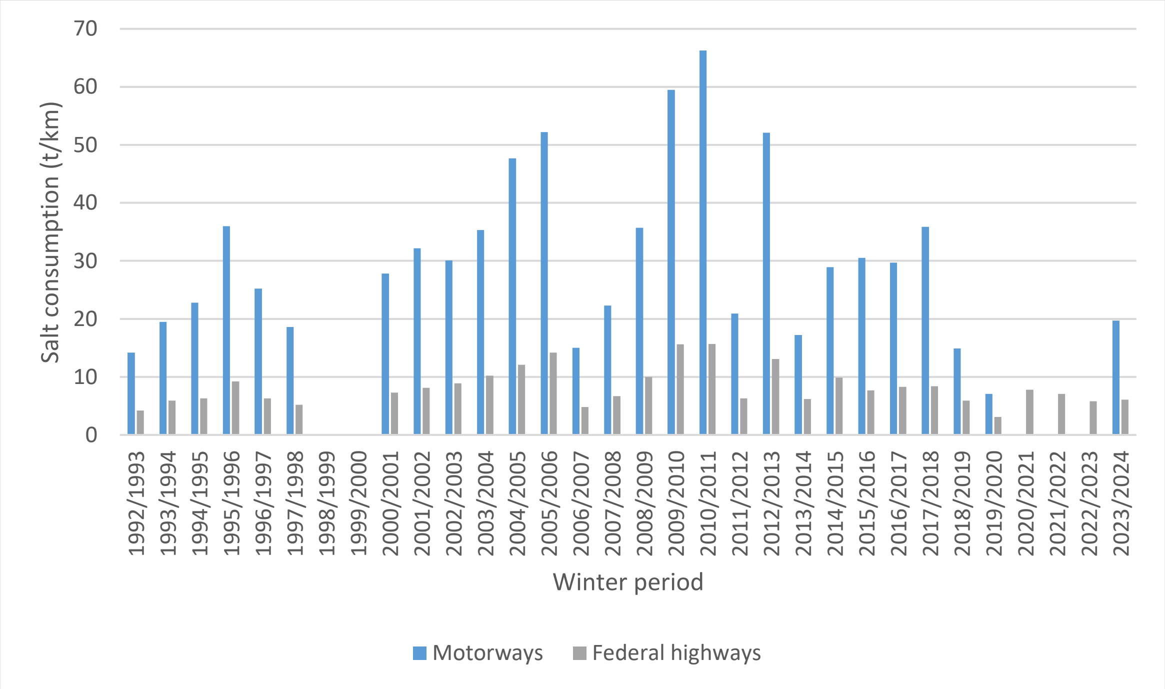


Figure 3: Specific salt consumption on national motorways (except privately operated motorways) and federal highways in Germany (for some years consumption was not reported)

The Nordics

In the Nordic countries, except for Denmark and the Faroe Islands, sand is spread in addition to salt. The amount of de-icing salt used in the Nordic countries is shown in Figures 4 and 5 [8]. The data are not fully comparable, both between and within countries, as the roads salted over the periods have changed over time, and the actual length of road salted needs to be taken into account. Different assumptions mean that the figures cannot be compared between countries.

Available data for levels of salt consumption in Denmark apply to both State and County roads up to the winter of 2007/2008. After that the data only includes consumption on State roads. In Norway, the data covers consumption on both State and County roads up until 2018/19 when the definition of State roads was changed. From 2019/2020 onwards, State roads also include footpaths and cycling paths. Sweden has had some problems with the reporting of salt and sand consumption, the Swedish Transport Administration is working on solving it, but as of 2018/2019 the data must be taken with a pinch of salt. Due to the new reporting method only 60% of the areas are included in the 2021/2022 data and only 80% in the 2022/2023 data.

The picture differs across the individual countries. In Norway, salt consumption can vary slightly from season to season, but the trend is that both salt and sand consumption has increased over time. In the last very mild winters, salt consumption was low. In Sweden there has been a lower consumption of salt in recent years, while sand consumption has increased.

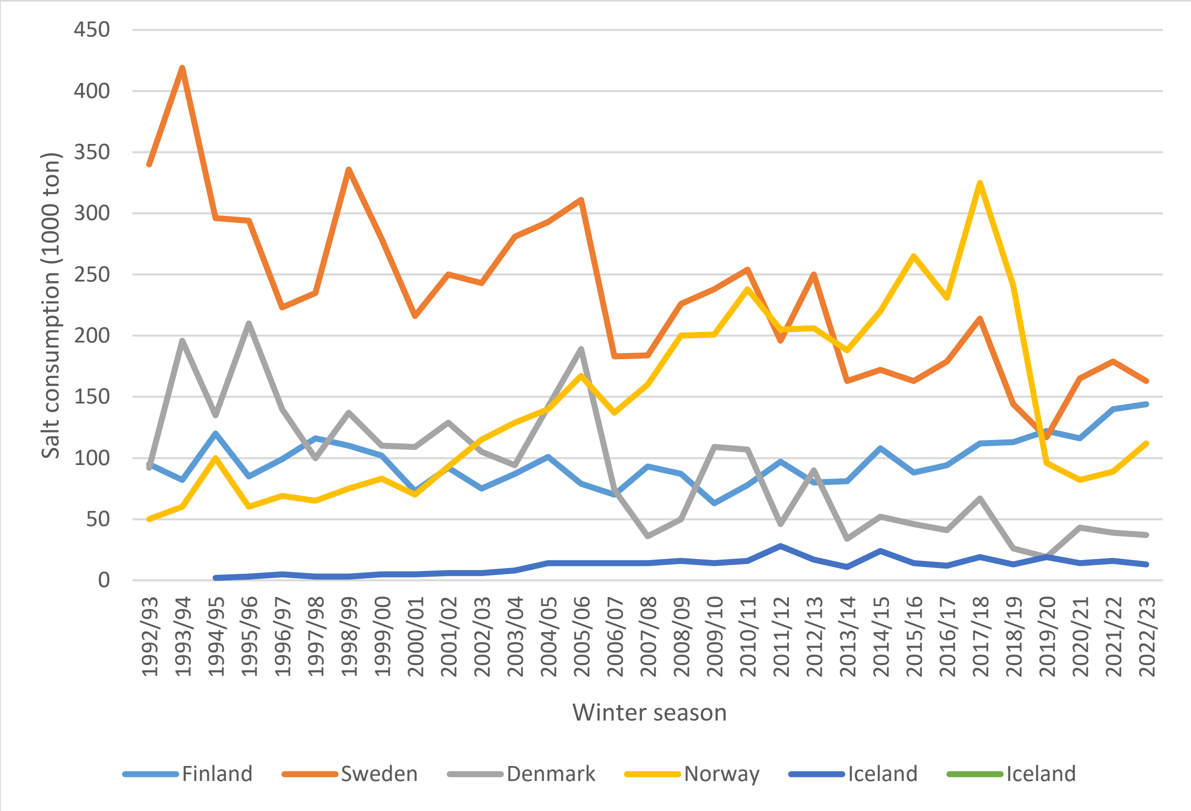


Figure 4: Salt consumption in the Nordics

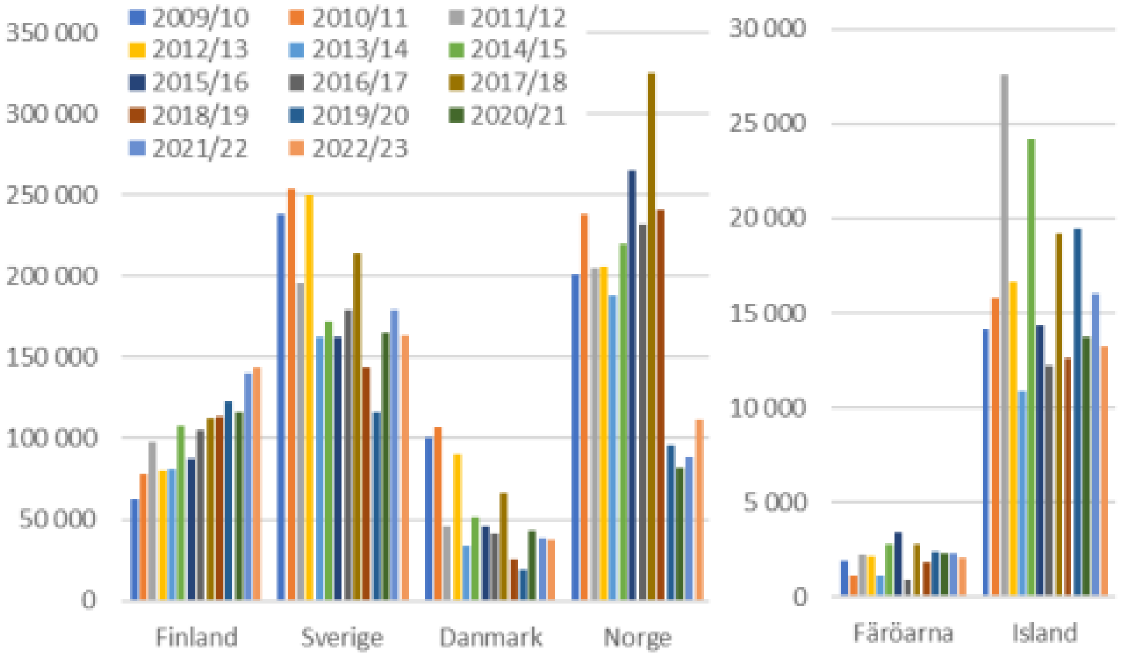


Figure 5: Salt consumption in the Nordics since the 2009/2010 season (ton)

The highest specific salt consumption (ton/km) can be found in Denmark and Norway (Figure 6).

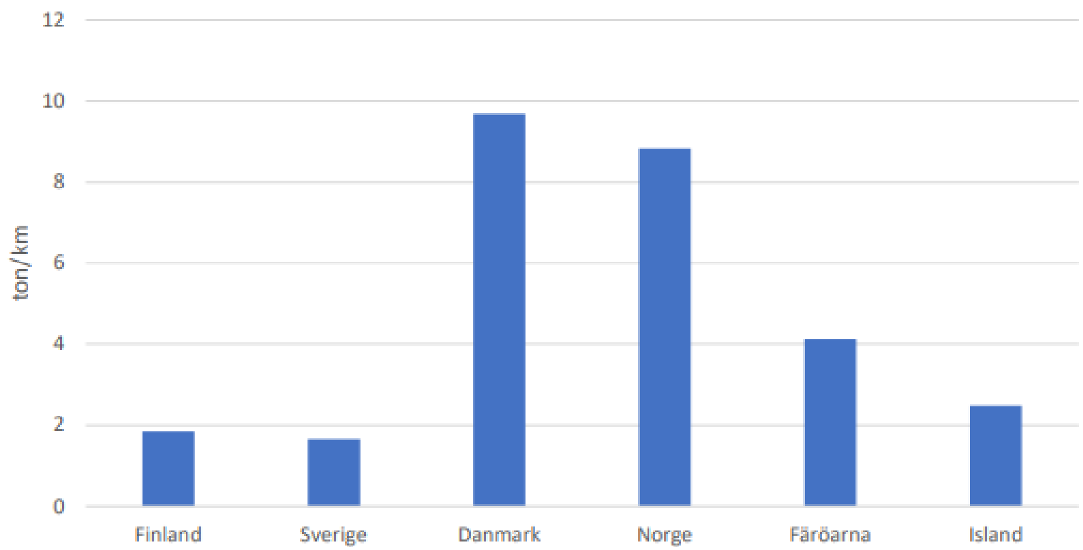


Figure 6: Salt consumption/km state road winter season 2022/2023

Significantly more sand is spread on winter roads than salt (Figure 7).

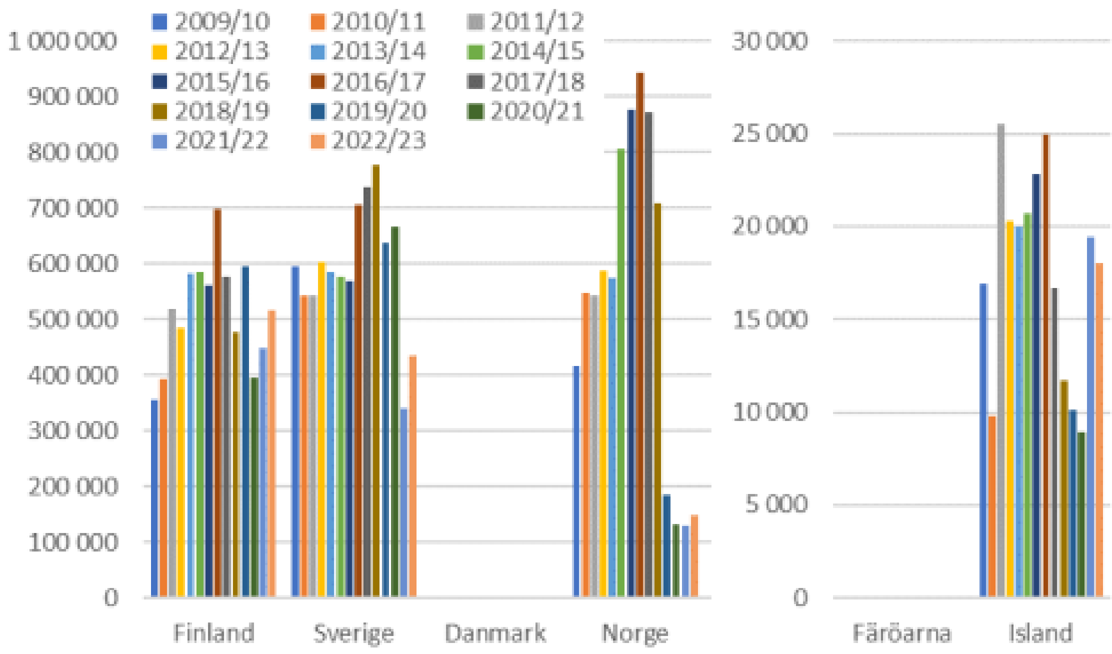


Figure 7: Sand consumption in Scandinavian countries (ton)

Scotland

In the period from 2010 to 2019, individual peak salt consumption was recorded on roads in Scotland, but the trend is neither increasing nor decreasing (Figure 8) [9].

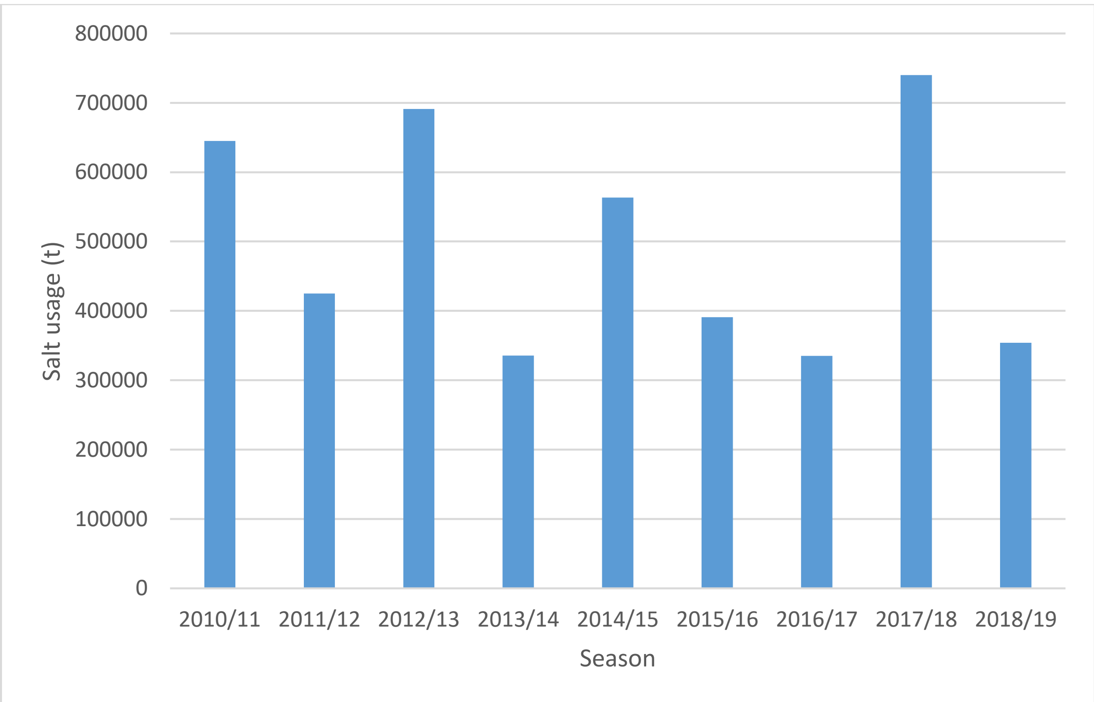


Figure 8: Salt consumption on roads in Scotland

Switzerland

Switzerland is a region that is close to or in the Alps. Consumption statistics show a clear upward trend for the years 1993 to 2023 (Figure 9) [10]. The main reasons for this are the strong expansion of national roads and the extended winter service times that are expected by the population. Switzerland exclusively uses vacuum salt from the Swiss Saltworks.

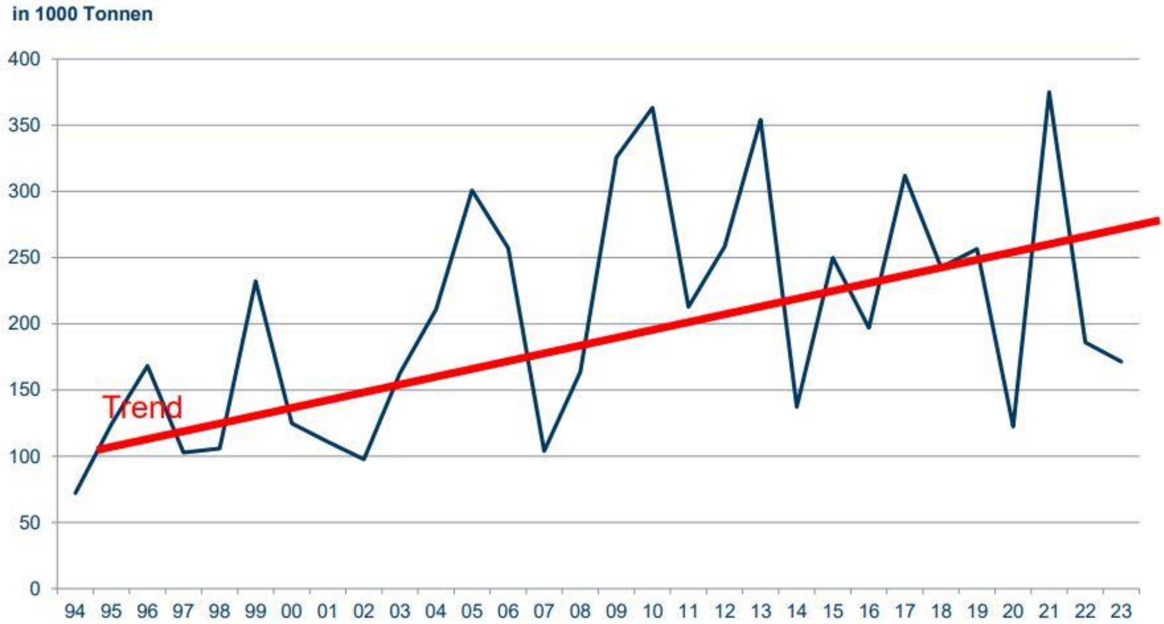


Figure 9: Total salt sales for de-icing in Switzerland

The example of Nationalstrassen Nordwestschweiz AG (NSNW) shows the extent of brine use in winter service across the motorways in northwestern Switzerland (A1, A2, A3, A5, A18 and A22).

45 winter service vehicles look after 230 km of roads with bridges, tunnels, and rest areas. On average, 4,000 tons of salt and 2.5 million litres of brine (21%) are required in winter. Particularly noteworthy is the large amount of brine used in relation to dry salt (Table 1). The brine is picked up ready for use from the nearby Swiss salt factories [11].

Table 1: Salt and brine usage on the National roads in northwestern Switzerland

Year	2021	2022	2023
Salt (tons)	3,776	2,412	1,226
Brine (liter)	3,729,126	2,251.318	1,873,766

Road salt application in European countries (CEDR Call 2016)

The Conference of European Road Directors (CEDR) research programme, saw several national road administrations (NRAs) report a conflict of interest between environmental concerns regarding the effects of de-icing agents and their task of protecting the national road network and enabling the efficient transport of goods and people. NRAs in the Nordic countries tended to be more concerned than their counterparts in Central Europe. One might assume that this is due to climatic conditions where the longer duration of winter conditions requires a longer application of road salt. It is difficult to make comparisons between different countries because reported usage depends on the length of roads served, as well as the levels of organisation in each country in terms of the type of roads included, etc. However, the climate in the Nordic countries clearly results in a longer road salt application season, which would increase the number of exposure days.

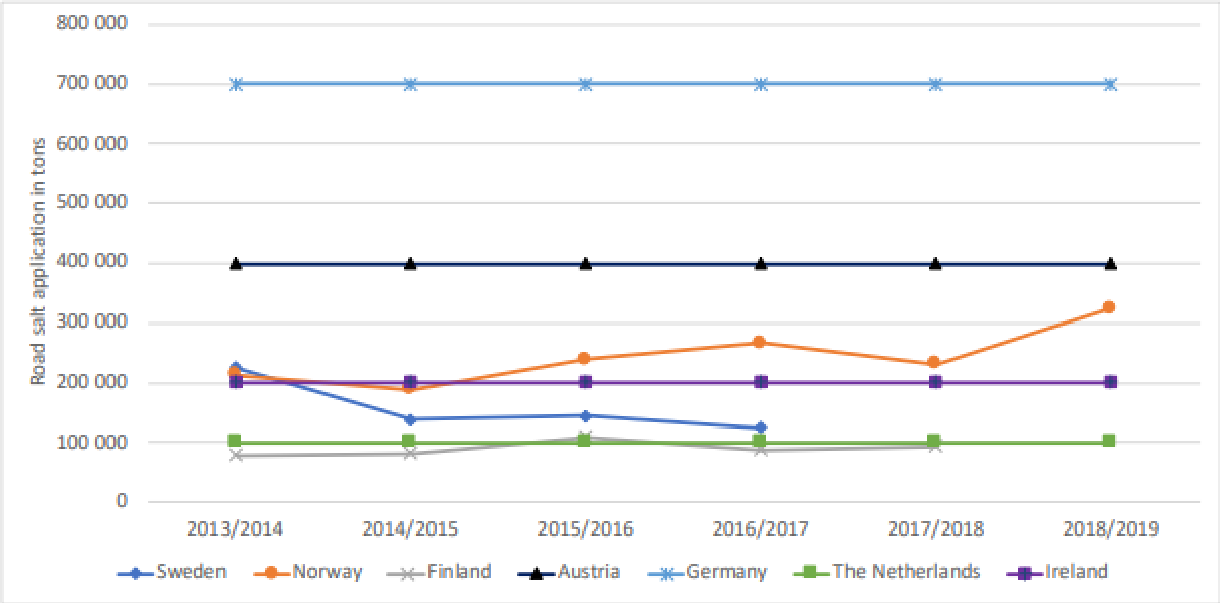


Figure 10: Road salt consumption on a seasonal basis for the seven participating NRAs. Germany, Ireland, and Austria only reported average annual values, and the Netherlands reported a range from 40000-160000 tons/year where 100000 was used as the mean of the range.

The comparison of annual consumption between the NRA shows a stable to slightly increasing trend. These reported numbers are not normalised to salted road kilometres and therefore cannot be used to compare salt application rates. However, the consumption data shows consistency with the general increasing concern that application rates show a steady or slightly increasing trend (Figure 10) [12].

USA

The US Geological Survey reports total consumption of de-icing salt by government (federal, state, local), commercial, and others in its annual publications "Mineral Summary Salt" and "Minerals Yearbook Salt" [13].

The East Coast and Midwest of the United States are the primary regions for de-icing salt consumption. Salt needs are met from U.S. mines and foreign sources.

In the period from the mid-90s to today, there has been an increasing trend in salt consumption (Figure 11). The quantity of salt consumed for road de-icing each year was directly related to the severity of the winter weather conditions. Salt consumption in some winters was influenced by the La Niña pattern. Long-range forecasting of salt consumption in this application is extremely difficult because of the complexities in long-range weather forecasting.

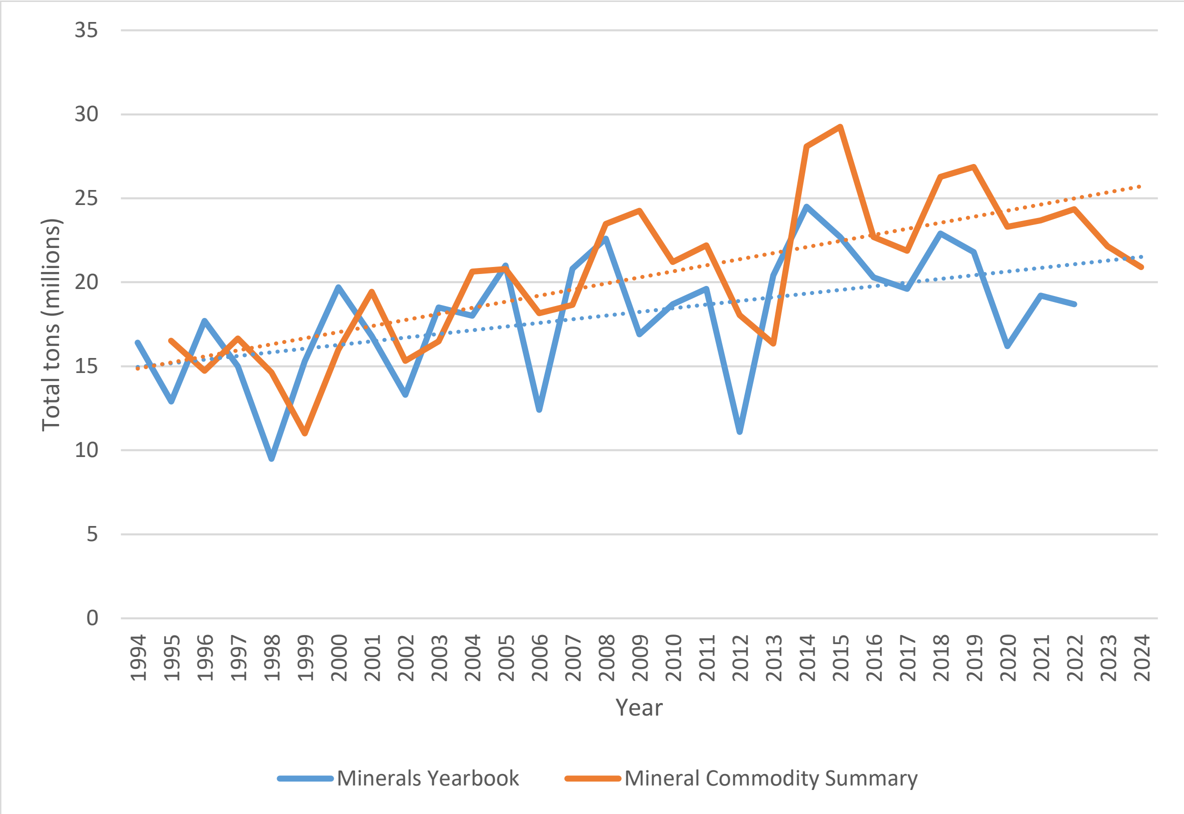


Figure 11: Total tons of salt used for ice control in the U.S. (numbers also include amounts for soil stabilisation)

Influence of climate change on winter road maintenance

The warming trend in the cold season will continue throughout Europe until the end of the century. Due to natural fluctuations, there may still be cold winters in the future, but these will become less frequent. Climate calculations also indicate a widespread increase in winter precipitation. However, due to higher temperatures, most of this will likely fall in the form of rain.

Although it is to be expected that the number of frost and ice days in European countries will decrease in the future, this does not mean that their number will fall to zero (examples for Germany see Figures 12 and 13) [14].

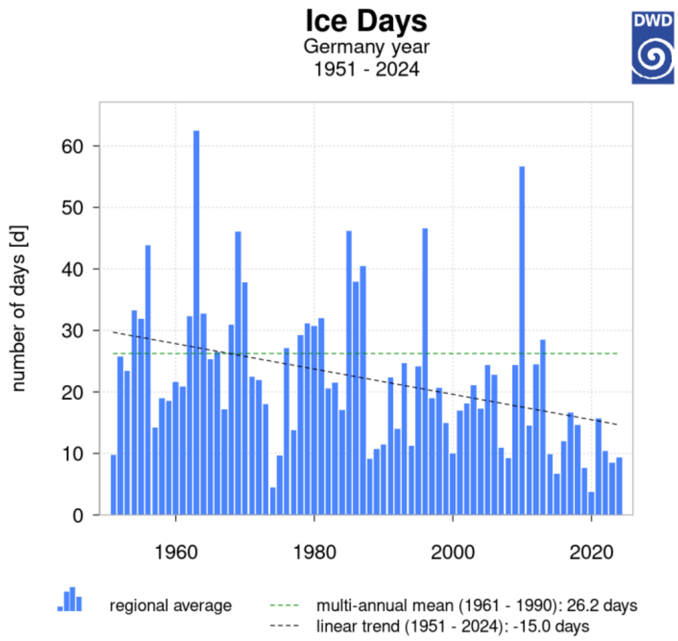


Figure 12: Ice days in Germany (an ice day is a day on which the maximum air temperature is below freezing point (below 0 °C), i.e. there is continuous frost)

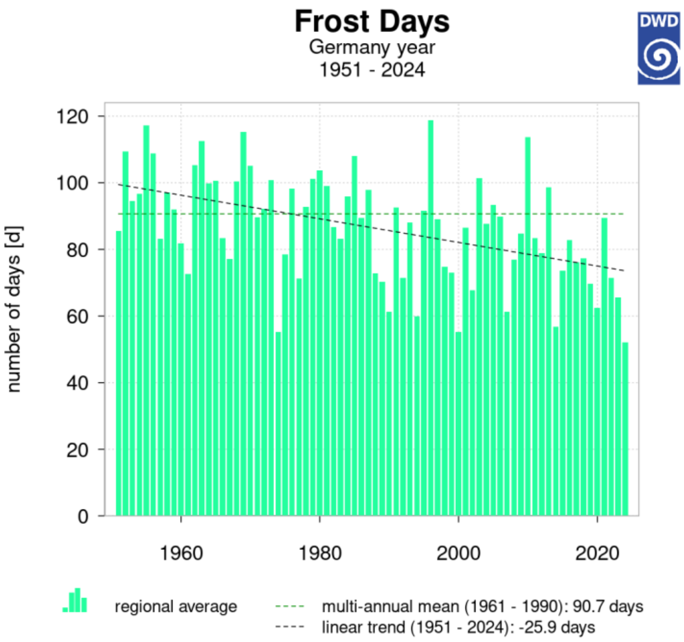


Figure 13: Frost days in Germany (a frost day is a day on which the minimum air temperature is below freezing point (0 °C) (ignoring the air temperature maximum). The number of frost days is therefore greater than or equal to the number of ice days on which continuous frost prevails. The number of frost days complements the statements about the severity of a winter, which is primarily determined based on the number of ice days.)

Therefore, it is also important to continue to adapt to possible cold extremes – in order to avoid delivery bottlenecks with salt, for example. As mobility behaviour changes, adjustments must also be made to winter service - for example in planning a possible increased provision of resources, the storage of a salt reserve and the expansion of the use of grit in the cycle path network. In the construction sector, it should be borne in mind that the increase in the amount of wet snow can, for example, lead to an increase in snow loads on roofs.

Meteo France has forecast the future development of frost and ice days for Strasbourg (Figure 14). Figure 15 shows the development of winter precipitation [15]. This confirms the decreasing trend in frost and ice days and the increasing trend in precipitation.

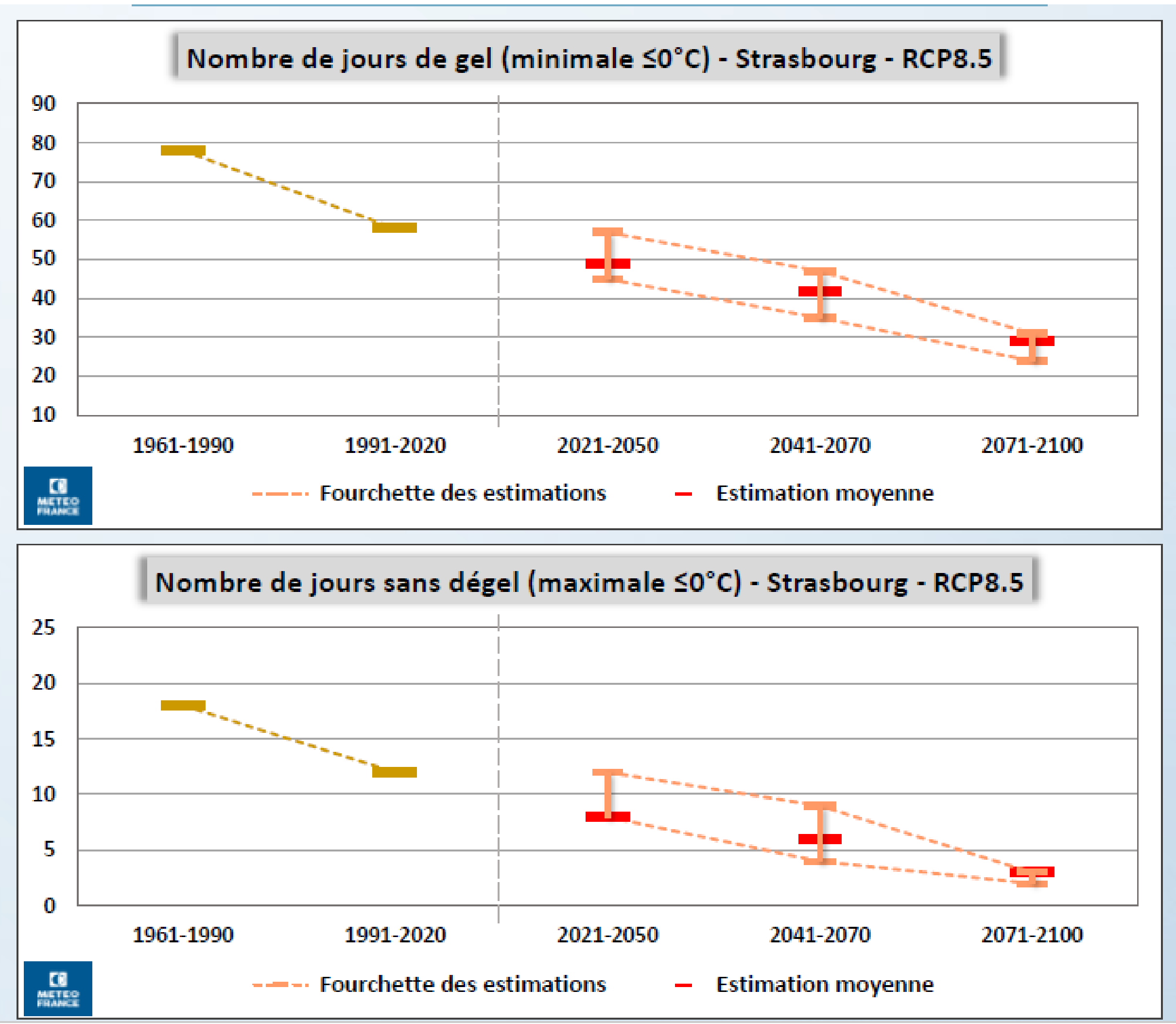


Figure 14: Development of frost days (top) and ice days (bottom) in Strasbourg (France) in the period 1961-2100

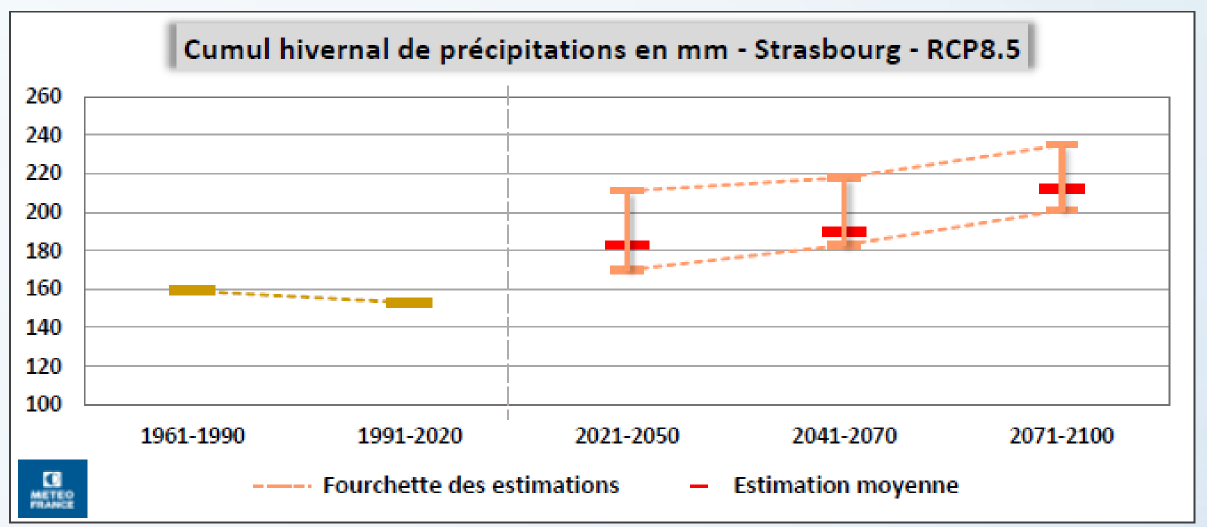


Figure 15: Development of total winter precipitation in Strasbourg (France) in the period 1961-2100

Over the past 60 years the UK's climate has been shifting due to climate change. However, analysis by the Met Office reveals that the shift has not' been even across the UK, with some regions experiencing more rapid change than others. Comparing two 30-year periods (1961-1990 and 1991-2020), the number of days of air frost (when the air temperature drops below 0.0 °C) has reduced on average by 11.1 days. Several areas across the UK have seen the annual number of air frost days fall by 14 days per year, including: Derbyshire, Northamptonshire, Northumberland, Nottinghamshire, Rutland, Shetland, Staffordshire, County Antrim and County Londonderry [16],

The UK Climate Resilience Programme, co-led by the Met Office, ran from 2019 to 2023 and produced various infographics to help communicate its outputs (Figure 16).

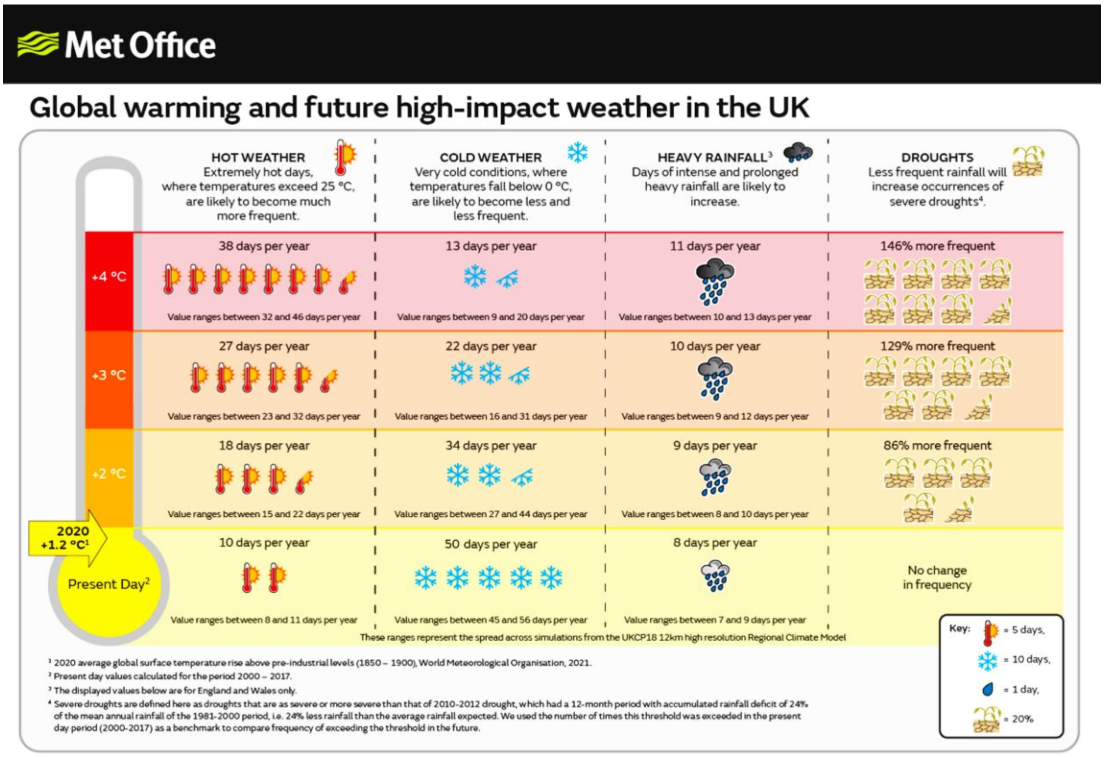


Figure 16: Global warming and the impact on frost days in the UK

Analysis of the Met Office UK Climate Projections reveals that climate change is expected to markedly decrease the number of ice days.

Currently, most locations in the UK receive a number of ice days each year, but if greenhouse gas emissions are not curbed, these could become very rare in southern England by the 2040s. And although they are still expected to occur further north – especially in upland areas – the frequency will reduce everywhere.

Over the past three decades, the average coldest day in the UK was -4.3 °C. If emissions continue to accelerate, leading to a global temperature rise of 4 °C, then the average coldest day in the UK would remain above 0 °C across most of the country throughout winter. Even if global emissions are reduced dramatically and world temperatures rise by 2 °C, the average coldest day in the UK is likely be 0 °C (Figure 17) [17].

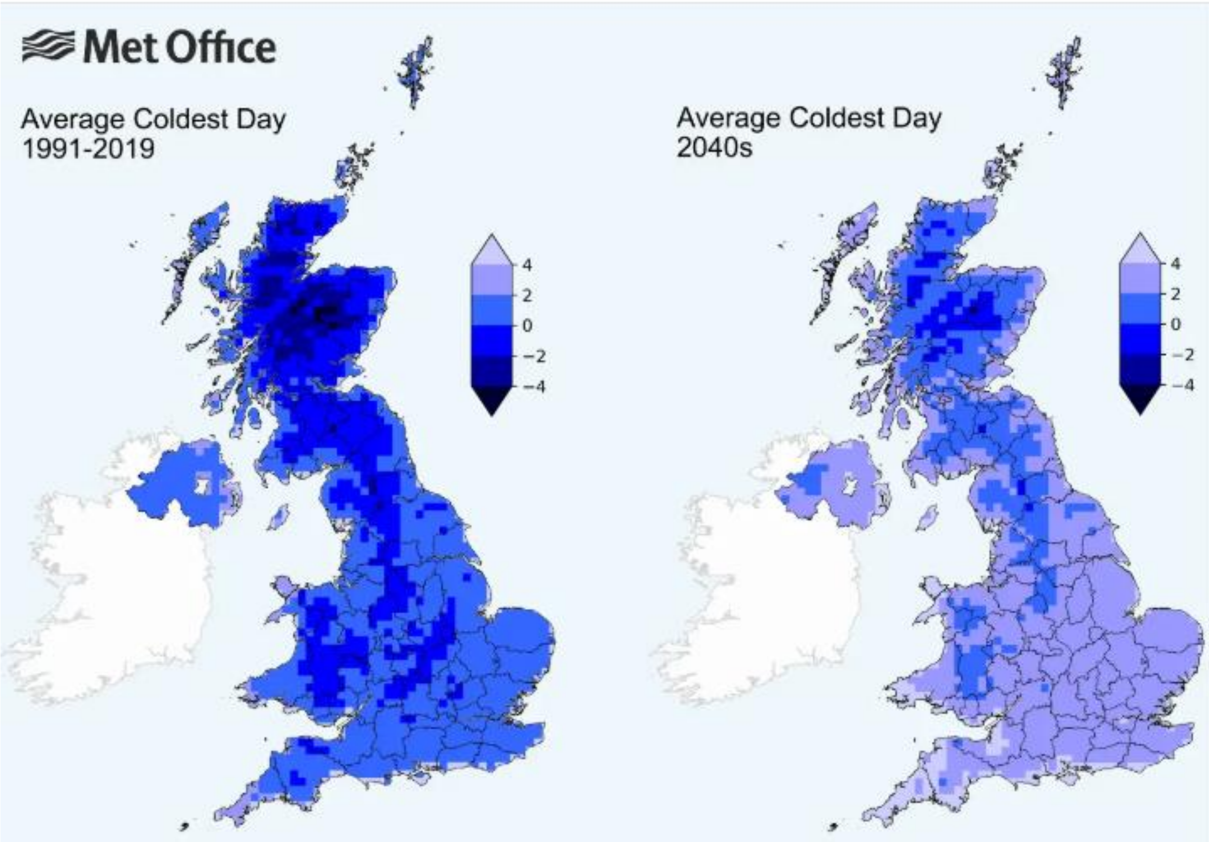


Figure 17: Average coldest days in the UK

4. ENVIRONMENTAL IMPACTS OF DE-ICING WITH SALT

- LCA studies are providing important insights into the environmental impact of winter service
- While the process of salt spreading is responsible for the most energy consumption and CO2 emissions, salt itself is found to have a positive environmental profile compared with other de-icer options
- New technologies and approaches offer significant potential to reduce the quantities of salt spread

Life cycle assessment of winter road maintenance

A German research project developed a simple method for life cycle assessment of winter road maintenance and made it available to interested parties in the form of an intuitive Excel tool ("ÖkoWin"). The road winter service considered in the project included winter service on out-of-town roads, especially motorways and federal highways [18].

The ÖkoWin tool enables the creation of individual life cycle assessments in six steps. The life cycle assessment is carried out in relation to a functional unit to be determined according to the question, which is a reference value with a spatial and temporal component, for example the winter service activities for the entire litter area managed over a specific winter period.

The primary energy consumption and greenhouse gas emissions determined in a life cycle assessment must be related to a functional unit. This functional unit could, for example, be the entire winter maintenance activities of a road maintenance depot in a single winter season. However, other functional units can also be used as a reference value, e.g., 100 km of road on which winter maintenance is carried out by a road maintenance depot in a particular winter. In any case, it must be defined for which spatial and temporal scope of the winter maintenance activity the primary energy consumption and greenhouse gas emissions are to be determined.

The processes that cause the greatest emissions in winter road maintenance, especially greenhouse gases, were determined for a typical highway maintenance depot, (Figures 18 and 19).

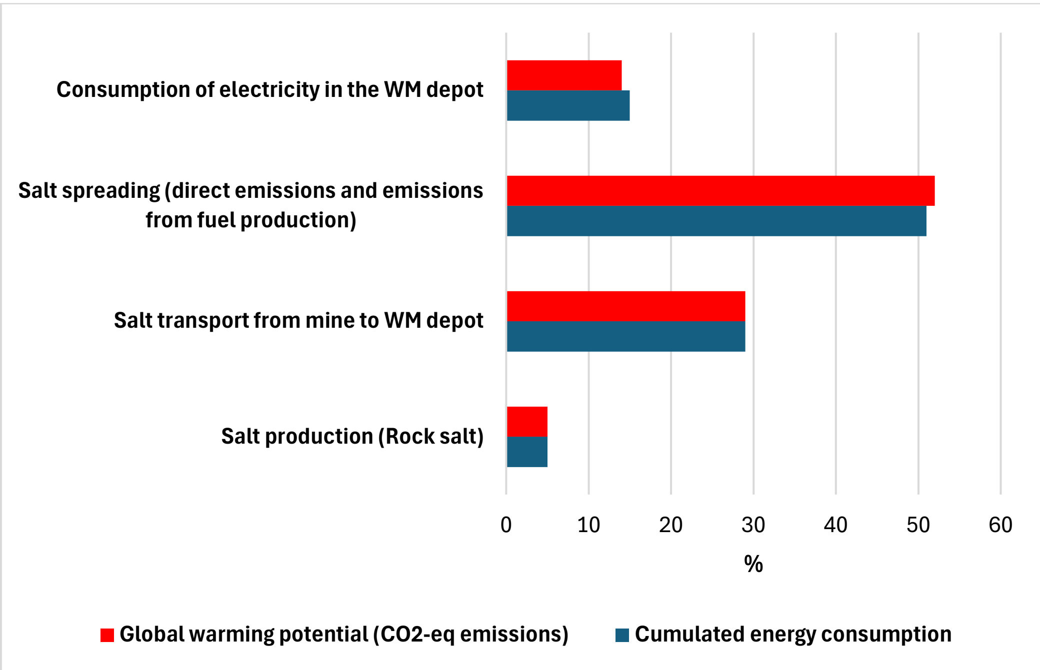


Figure 18: Global warming potential and cumulated energy consumption in % for the relevant impact categories for a German motorway winter maintenance depot (winter 2022/23, road area 1,302,264 m^2, salt consumption 930 t)

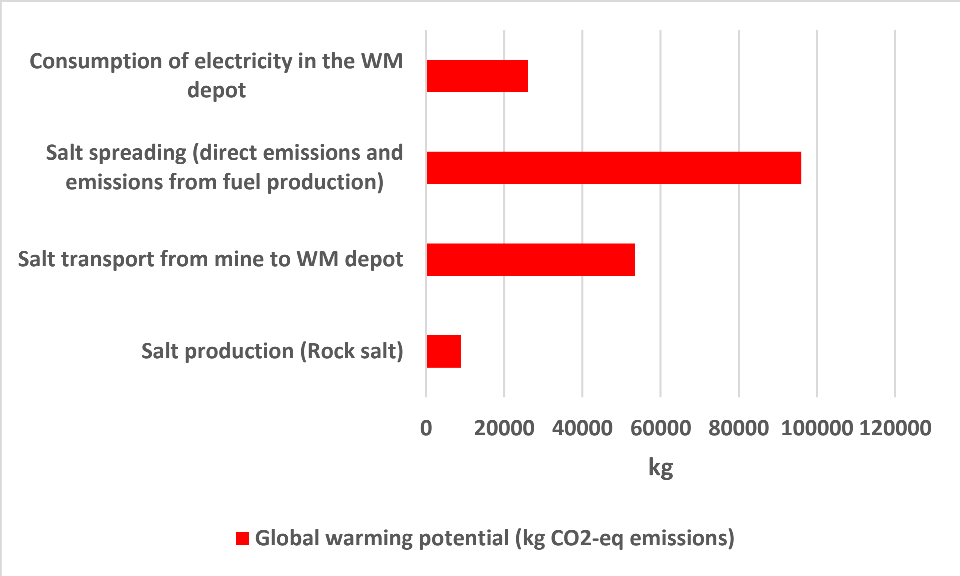


Figure 19: Global warming potential (kg CO2-eq) for the core processes for a German motorway winter maintenance depot (winter 2022/23, road area 1,302,264 m^2, salt consumption 930 t)

The core process of salt spreading is responsible for the greatest consumption of energy and also the greatest CO_2 emissions. The transport of salt from the saltworks to the depot is the second highest. Electricity consumption in the depot also plays a role, with the production of salt being the least important in terms of energy consumption.

In Sweden, the production and transport of road salt used for road maintenance accounts for approximately 18 percent of emissions resulting from infrastructure maintenance (Figure 20). The figure shows the distribution of greenhouse gas emissions linked to road maintenance in basic contracts and is calculated on the average of 10 selected contracts. Sweden has no natural mineral deposits that can be used as road salt and the climate is not adapted to producing road salt from seawater. As a result, Sweden imports the entire volume of road salt from central Europe and the Mediterranean countries [8].

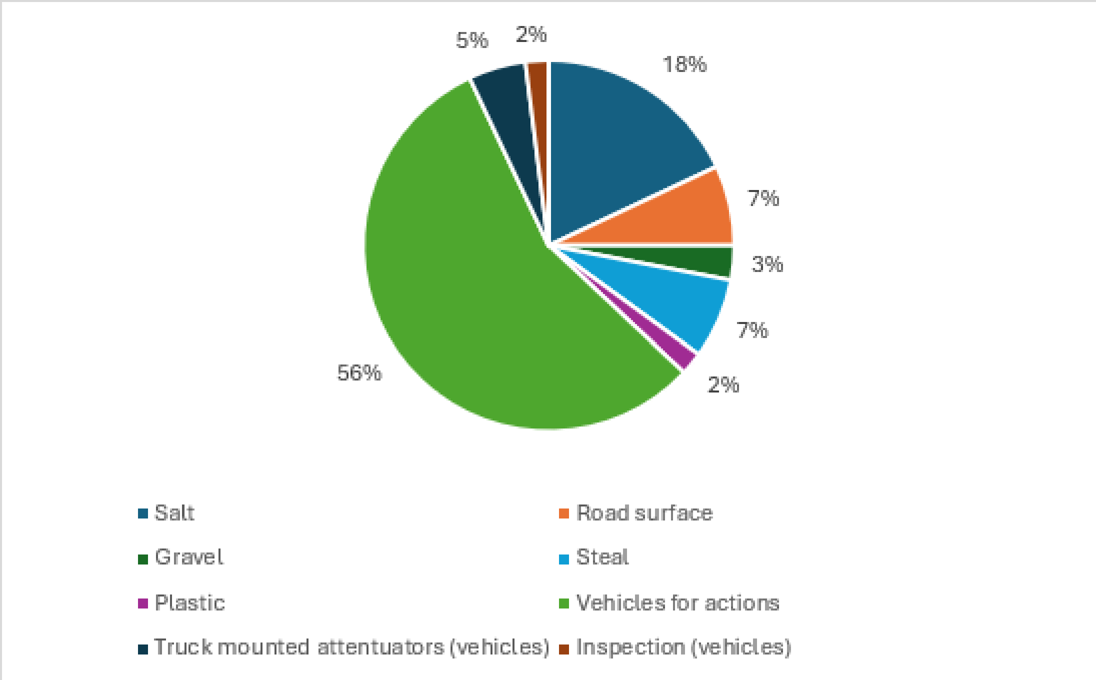


Figure 20. The distribution of greenhouse gas emissions linked to road maintenance in basic contracts, calculated on the average for 10 selected basic contracts. (Image from WSP report, Climate Calculation Basic Contract Road, mapping of greenhouse gas emissions 2018-06-07)

Chloride migration

The Evian Impluvium is the preferential infiltration site of the Evian hydromineral deposit in France. It is recognised as being of international importance and is protected from chlorides through a framework agreement on the environmental control of road maintenance in winter. The Association for the Protection of the Evian Mineral Water Impluvium (APIEME) is testing and implementing an action plan in partnership with the Department of Haute-Savoie and the 13 municipalities which are members of APIEME [19].

For many years, the APIEME municipalities have undertaken various actions to reduce the quantities of sodium chloride released into the environment. The organisation’s documents and salting plans, implemented with strong political support, prove to be highly effective at reducing the quantities of salt spread. The actions implemented have already reduced salting by 35 percent within the territory since the 2011 framework agreement - by 42 percent on departmental roads and 19 percent on municipal roads (APIEME, 2021).

Centre for Studies and Expertise on Risks, the Environment, Mobility and Urban Planning (CEREMA) came up with a summary of the actions to be carried out per municipality as well as an action sheet listing various implementation choices. APIEME and its directors chose three priority actions for 2022: update or create winter service plans, a campaign to adjust and calibrate salt spreaders, and assistance with winter management equipment.

A salting reduction potential has been calculated for each municipality based on the implementation of the action plan. It can therefore be seen as an objective and a follow-up indicator. This potential involves comparing salt consumption over the past ten years (in relation to the output numbers and the treated surface) with the theoretical quantities of salt spread once the actions have been implemented. The average salting reduction potential based on the implementation of the action plan is 60 percent.

To understand how runoff chlorides migrate into the adjacent environment, Clear Roads has started a study for determining the migration of chloride-based de-icers through different soil types. An understanding of how chloride de-icers move, disperse in, or migrate through, varying soil types would help to identify sensitive areas that may need adjustment to chloride deployment rates to help protect public and private aquifers [20].

The goal of this project is to provide winter maintenance teams with a thorough understanding of how sodium chloride, calcium chloride and magnesium chloride migrate through different soil textures – and how agricultural-based inhibitors affect that process. The deliverables – specifically a series of one-page fact sheets based on the results of a controlled testing programme – will assist agencies in developing localised maintenance treatment plans.

Microplastics

The results of a Swedish study on microplastics in snow in an urban area show that tire wear-related microplastics (rubber polymers) tend to be present in higher concentrations on and near the road surface. Other plastics have a less clear connection to traffic. Along a salted bicycle path, a raised layer of polypropylene was found in the surface layer of snow, which makes up the brush of the sweeper and salting machine. The study does not mention any entry of microplastics from road salt [21].

Air quality

The new EU air quality directive is intended to contribute to the bloc's target of zero pollutants by 2050 [22].

If PM10 limits are exceeded, any concentrations of de-icing salt or grit sand contained therein can be subtracted from the measured PM10 concentrations. The PM10 concentrations of de-icing salt and sand are therefore not taken into account when assessing whether PM10 limits are met.

The prerequisite for this is that the use of salt or sand is limited to the minimum necessary for successful winter maintenance.

EU member states now have the following tasks:

- For a given year, identify zones within which limit values for PM 10 are exceeded in ambient air due to the re-suspension of particulates following winter-sanding or winter-salting of roads,
- provide the Commission with lists of any such zones, together with information on concentrations and sources of PM 10 in such zones,
- provide evidence demonstrating that any exceedances are due to re-suspended particulates and that reasonable measures have been taken to lower such concentrations.

By 31 December 2026, the Commission shall provide, by means of implementing acts, technical details for the methodology for determining contributions from the resuspension of particulates following winter-sanding or winter-salting of roads.

5. DE-ICING WITH SALT AND ITS ROLE IN A GREEN TRANSITION AND SUSTAINABILITY AGENDA

- Significant opportunities exist in decarbonising winter service - from salt production through to transportation and spreading
- Alternative technologies offer significant potential to power winter service – from electric vehicles through to hydrogen, biodiesel and fuel cells. Harnessing wastewater from industrial processes has potential to deliver reuse and circularity

Decarbonisation and Winter Road Maintenance

The UK Government has national and international commitments to reduce greenhouse gas emissions - including a stretching commitment to be carbon net zero by 2050. The infrastructure sector has a key role to play in this. As the government company tasked with operating, maintaining and modernising England’s motorway and all-purpose trunk road network (the ‘strategic road network’), National Highways has an important role to play in delivering these commitments. In July 2021, National Highways launched the Net Zero Highways Plan which sets out the target for maintenance and construction activities to be net zero by 2040.

National Highways is collecting data on carbon emissions from the supply chain construction and maintenance contractors through a carbon accounting tool. The data directly informs National Highways performance in relation to the 2040 target. The tool includes road salt and its transport to the site from the point of purchase [23].

The decarbonisation of winter service must focus on

- salt production,
- the transport of salt from the production site to the silos and warehouses of the winter service organisation,
- salt spreading (direct emissions and emissions from fuel production), and
- electricity consumption in the winter service depot.

Several options for the decarbonisation of salt production have already been implemented or announced: Use of electricity from renewable sources for the vehicles and machines underground as well as for mine ventilation; Vehicles used for solar salt harvesting can also be converted to drive with batteries or fuel cells; Evaporated salt plants can run on electricity from renewable sources or steam from power-to-heat systems, in addition to electricity and steam from waste incineration plants. Other options are biodiesel and e-fuels.

Rail and ship transport should be preferred over truck transport for the transport of salt to winter service depots, if appropriate logistics routes exist, and economic efficiency is guaranteed. In the future, trucks with battery and fuel cell drives will also be available.

A project in Germany has the goal of providing agencies that rely on diesel-powered maintenance fleets with a thorough understanding of the available technologies (batteries, e-fuel, hydrogen, biogas, fuel cells) and related operational considerations that would be impacted by a transition to a fleet powered by alternative technologies [24].

In general, road service trucks require comparatively little energy per day (battery-electric up to approx. 400 kWh, which can easily be charged overnight). Winter service poses a problem when there is prolonged snowfall. For battery-electric vehicles, the energy requirement can rise to around 1.5 MWh/d per truck, and it takes hardly any time to load.

The goal of the Clear Roads project in the U.S. was to document the available technologies, energy sources, practical considerations and other needs that state Departments of Transport may have in migrating their winter maintenance fleets to electric or alternative fuel vehicles [25].

Alternative fuel options, including biodiesel, natural gas, liquefied petroleum gas (propane) and battery electric vehicles, are available for medium- and heavy-duty trucks. Other developing options include renewable diesel, renewable natural gas, renewable propane and hydrogen. The use of alternative fuels in winter maintenance fleets, however, is currently limited. Two agencies reported using natural gas but are phasing it out due to high vehicle maintenance costs, fuelling station costs and availability. Several agencies use biodiesel blends in their fleets in cold months (B20 with B10). Other agencies are using a fuelling system that enables the year-round use of neat biodiesel (B100) in heavy-duty trucks, including snowploughs. Heavy-duty battery electric truck chassis that would perform snowplough duties were not currently available but are anticipated in the near term.

Circular Salt and Re-use

Many industrial processes, such as in the food industry, use brine (sodium chloride solution), which must then be disposed of as salt wastewater by discharging it into natural bodies of water or otherwise. To increase ecological sustainability, these dissolved salts could be used for winter service, thus saving salt overall.

The focus on environmental issues in recent years, has led to the emergence of a number of new ideas, as well as already developed and ready-made processes, that can produce various salts from waste products. These so-called "circular salts" offer benefits in that they use waste products that would otherwise be landfilled or backfilled in mines, and replace virgin products that are often transported long distances. The use of locally produced salt is expected.

In Sweden a 2-year industry project for the implementation of circular salt from a plant which processes fly ash was initiated in 2024. It will provide a knowledge base to be able to set requirements in procurements that lead to a competitive market. A reduction in the carbon footprint of road maintenance is expected. The demonstration project, which will last two winters, began in winter 24/25 with the adaptation of machines and equipment for district salt spreading. The effect of the salt will then be evaluated using road friction measurements using connected vehicles (Floating Car Data) in order to validate and evaluate the effectiveness of circular salt for de-icing. An important part of the project includes analysis and identification of adaptations that must be made to regulations and requirements to create the conditions for implementation [8].

A further example is the use of fermentation brine from a pickled gherkin manufacturer in Bavaria for winter service: The fermentation brine contains around 10 percent sodium chloride and, in the past, was disposed of by discharging it into a wastewater treatment plant. A development project has shown that it can be cleaned of suspended matter through sedimentation and filtration. The lactic acid formed during fermentation was neutralised with caustic soda and the brine concentration was then increased to 21 percent with additional dissolved salt [26].

In order to protect sensitive water habitats and groundwater, saline water from roads can only be discharged in small quantities over a longer period of time and into waters with sufficient runoff. However, suitable water bodies are not available everywhere, so large retention basins or long pumping sections have to be built, which is associated with high costs and land consumption. These structures are also complex to build and operate.

In cooperation with other research partners the Austrian Autobahnen- und Schnellstraßen-Finanzierungs-Aktiengesellschaft (ASFINAG) developed a technical test facility intended to remove the salt from the collected salty runoff of roads and reuse it. Two different processes are tested and compared with each other. One is based on electrodialysis, the second on the principle of reverse osmosis.

The result is pure water, which is free of salt and a salt concentrate that is collected in a tank. A certain concentration should be achieved so that the salt can be used again as brine for winter service. This means that significantly less de-icing salt ends up in the environment and reuse also has economic advantages [27].

6. INFORMATION AND COMPARISON BETWEEN DE-ICING WITH SALT AND ALTERNATIVES

- Salt continues to be the most commonly used de-icer in Europe
- Alternative de-icers present opportunities in specific situations and climate conditions
- Availability, cost and shortcomings such as corrosion must be weighed when considering alternative de-icer solutions
- Research has been exploring the opportunities for alternative options in sensitive areas and around sensitive structures.

Other chloride-based de-icers

Sodium chloride (salt) is the most commonly used chemical de-icer in Europe. It is suitable for the majority of the winter conditions, relatively low cost, and readily available. Calcium chloride ($CaCl_2$) and magnesium chloride ($MgCl_2$) are also used to a small extent.

Aqueous solutions of calcium chloride and magnesium chloride are used as alternatives to sodium chloride solutions in wet salt technology. However, in direct liquid applications with these solutions there is a risk that chemical slipperiness can arise due to the formation of hexahydrates on the road, which significantly reduce road grip. This occurs at low air humidity levels. Since it is not economic to have two different solutions for winter service - a $CaCl_2$ or $MgCl_2$ solution for wet salt technology and salt brine for direct brine application - it is recommended to use only salt brine for winter service [28].

Calcium chloride has a very low eutectic temperature of -55 °C. Therefore, solid calcium chloride, usually mixed with sodium chloride, can be effective in combating slipperiness on roads with temperatures lower than -15 °C. Such applications may be necessary in the Alpine region, for example.

Aside from the risk of chemical slipperiness, the greatest disadvantages of calcium chloride and magnesium chloride are the double input of chloride into the environment compared to sodium chloride. Calcium chloride is also classified as a hazardous substance. In addition, the costs of these chlorides, in both solid form and in solution, are significantly higher than for sodium chloride. The availability of calcium chloride and magnesium chloride is also far lower than that of sodium chloride.

Sometimes the suitability of potassium chloride for winter service is of interest. This chloride has a eutectic temperature of -10.7 °C, resulting in a lowest effective temperature of -5 °C (in comparison with sodium chloride at -15 °C). This means that potassium chloride could only be used for winter service in near zero degrees Celsius. Potassium chloride is more toxic to fish than sodium chloride and also costs several times the price of salt. For these reasons, potassium chloride is not used for winter maintenance in Europe.

Non-chloride de-icers

Transportation agencies continuously look to reduce salt use to avoid contaminating wells and waterways, causing corrosion on vehicles and infrastructure, and harming vegetation. Non-chloride de-icers could potentially serve as viable substitutes in winter maintenance operations, limiting these adverse effects. Several studies have been carried out on non-chloride de-icers [29-35].

For Europe, it is worth taking a special look at formates and acetates. Acetate-based de-icers include potassium acetate (KAc), sodium acetate (NaAc), and calcium magnesium acetate (CMA). Acetates provide a low effective temperature and have generally lower environmental impacts. Negatives are the damaging impacts to pavements (concrete and asphalt). Due to their higher cost, acetates tend to be used as airport de-icers and in areas where corrosion of metal is a concern. But they have a high impact on galvanized steel as they are corrosive, like formates.

Common formate-based de-icers include potassium formate (KFo) and sodium formate (NaFo). They are like acetates and are commonly used to de-ice runways at airports. However, formate-based de-icers are corrosive to galvanized steel and are expensive.

A comparison of acetates and formates with sodium chloride is provided in Table 2.

Table 2: Comparison of acetates and formates with sodium chloride

	NaCl	NaAc	KAc	CMA	NaFo	KFo
Eutectic Temperature	-21 °C	-17 °C	-60 °C	-28 °C	-22 °C	-54 °C
Practical Temperature	-15 °C	-17 °C	-20-25 °C	-3 °C	-10 °C	-10 °C
Melting Capacity	++Yes, melt most snow of de-icers	-Slow effect	-Slow effect	-Not so much & -Very slow & -Not ice	-Slow effect	+Fairly good -Not ice (brine)
Dries up at road	+Yes	-No	-No	-No	-No	-No
Relative Cost*	1	10-15	10-20	10-15	10-15	15
Impacts						
Ecological Toxicity	- Chlorides in groundwater - Sodium affects soil structure	+ Bio-degradable - Consumes oxygen in the soil and water	+ Bio-degradable - Consumes oxygen in the soil and water -Toxic to some aquatic life	+ Bio-degradable - Consumes oxygen in the soil and water -Toxic to some aquatic life	+ Bio-degradable - Consumes oxygen in the soil and water	+ Bio-degradable - Consumes oxygen in the soil and water
Asphalt Pavements	Low	Moderate	Moderate	Moderate	Low to Moderate	Low to Moderate
Concrete Pavements	Low	Moderate to High	High	Low	Moderate	Moderate
Mild Steel Corrosion	High	Low	Low	Low	Low	Low
Galvanized Steel Corrosion	High	High	High	High	High	High

*Different application rates are necessary.

Potassium carbonate (eutectic temperature: -18 °C) is a synthetic de-icer made from potassium chloride. Problems with this de-icing material include increased corrosion of gritting vehicles and high alkalinity, which can cause chemical burns when handling. The cost of potassium carbonate is about 10 times higher than sodium chloride.

Ethylene glycol (eutectic temperature: -42 °C) and propylene glycol (eutectic temperature: -60 “C) have a satisfactory de-icing effect and are non-corrosive. Glycols can negatively impact the environment (increased Biochemical Oxygen Demand). These flammable products require increased security efforts. They also reduce the surface tension of the water, which means that meltwater can penetrate into the finest hairline cracks in concrete pavements and damage them when they freeze. The product cost is much higher than salt. Glycols, as individual components or in mixtures, are only used to de-ice aircraft.

The European Committee for Standardisation (CEN) produced the Technical Specification CEN/TS 16811-3 for other liquid and solid de-icing agents [36]. It describes the requirements for de-icing agents with different properties from de-icing agents according EN 16811-1 (Sodium chloride) and EN 16811-2 (Calcium chloride and Magnesium chloride), and which are used for specific services on roads. Testing methods are included in the Technical Specification. The multitude of products which can be used in winter maintenance - liquid or solid, natural or industrial produced substances – requires the defining of performance criteria with which the products have to comply. These criteria are used to assess the usability of the de-icing products while taking into consideration all aspects of the safety of the road user, the protection of the environment and of the road conditions. The Technical Specification is suitable for comprehensively testing alternative de-icers. CEN intends to revise the Technical Specification and convert it into a European Standard.

Use cases of non-chloride de-icers

In Europe, there are few known uses for non-chloride de-icers outside of airports. The chemicals used are potassium formate, potassium acetate and potassium carbonate. These chemicals are used in sensitive, limited urban areas. They are not used on a large scale like sodium chloride.

In Copenhagen, potassium formate with a corrosion inhibitor is used, but only on the Øster Allé (length 1.1 km) with sensitive avenue trees. Otherwise, Copenhagen sprays the city area with sodium chloride, the main spreading agent in the city.

In Cologne, formate is used on a few road sections with sensitive vegetation or in the vicinity of certain buildings [37].

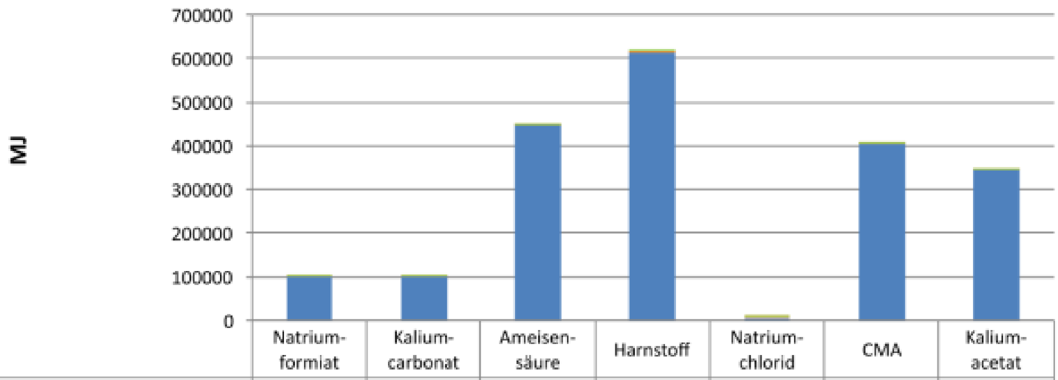
National Highways in England sprays potassium acetate liquid on bridges or sensitive structures. Rock salt is used on the vast majority of routes [38].

Transport for London (TfL) generally uses natural rock salt on its roads to help prevent icy conditions and keep roads safe for use. This is standard practice in the UK. TfL has used calcium magnesium acetate but its use was discontinued due to operational issues. There are concerns that it may leave a slippery film which could be hazardous to cycles. TfL have also used potassium acetate on cycle super highways but it was discontinued due to cost issues. Potassium acetate liquid is an effective de-icer but the most expensive solution (approx £1 per liter) [39].

The current Hamburg Road law completely forbids the use of de-icers on cycle paths. If cycle paths are slippery, only abrasives, such as sand, gravel, grit, expanded clay, ash or granules can be used. Abrasives have the advantage that they have no negative effects on plants. However, cyclists often criticize the road environment. In addition to high spreading and clearance costs, there is also poor efficiency in the event of ice formation or thaw and possible damage to the bike (especially after winter) as a result of grit or gravel.

As part of the E-WIN project, extensive research was carried out into possible alternative non-chloride de-icers, which were searched for and listed. These were then sorted according to different criteria, checked and subjected to further tests after a pre-selection – such as taking into account de-icing performance and soil compatibility. A life cycle assessment of the de-icers (Figure 21), calculated their use in one-time spreading of the entire path network. From the overall assessment of the de-icing materials examined, a relatively clear picture emerges regarding the environmental impact categories: Sodium chloride causes the lowest carbon emissions and has the lowest primary energy requirements.

At the end of the laboratory and preliminary investigations, four solutions of de-icing agents were tested: Sodium formate 25 percent, potassium acetate 30 percent, calcium magnesium acetate 25 percent, and sodium chloride 20 percent (as reference). The tests were very promising for the alternative de-icers. However, approval for the permanent use of non-chloride de-icers on cycle paths was not granted by the responsible authorities in the city of Hamburg [40].



	Natrium-formiat	Kalium-carbonat	Ameisen-säure	Harnstoff	Natrium-chlorid	CMA	Kalium-acetat
Reinigung (Strom) in MJ	40,7	40,7	40,7	40,7	40,7	40,7	40,7
Betrieb LNF Diesel M+N1-I Euro-6ab in MJ	429,4	429,4	404,1	687,0	381,7	381,7	381,7
Betrieb Vorkette in MJ	524,4	524,4	493,6	839,1	466,2	466,2	466,2
Herstellung in MJ	100539,7	100539,7	448072,8	614190,0	6982,0	403639,5	344848,6

Figure 21: Consumption of primary energy for de-icers (MJ)

The city of Vienna used potassium carbonate down to -8 °C in a mixture with expanded clay in the Vienna Forest area and on the Ringstrasse in the 1st district. The aim was to avoid chloride contamination of the soil and subsequent damage to sensitive vegetation. Potassium carbonate is hygroscopic and clumps together with water and dulling materials. This can block the transport of grit on the gritting vehicles. The city has now replaced the potassium carbonate with a solution of potassium formate. This is spread in sensitive urban areas using a dual-liquid spreading machine. The spreading vehicle is equipped with a tank for brine and a tank for formate solution. The appropriate liquid is applied as required.

In Chambéry, France, potassium carbonate is used as an exception in pedestrian areas covered with natural stone floors or concrete slabs sensitive to de-icing salt and in parks [37].

7. INNOVATION, ESPECIALLY IN TERMS OF OPTIMISATION OF SPREADING SALT

- There has been significant evolution in the understanding of the different impact and advantages of various de-icing methods over the past years
- Spreading techniques, vehicle types, timing and the product used all play a role in delivering an optimal winter service
- Countries use a combination of pre-wetted salt, dry salt and brine at different mixtures in winter service depending on the specific conditions and temperature
- Establishing the optimal levels of salt/pre-wetted salt/ brine/grit to use on roads in different conditions can deliver marked savings in terms of product and costs, while also delivering optimal service
- Use of sophisticated, multi-function spreaders drives both efficiencies and economies
- Accurate information on weather conditions and trends is playing an increasing role in winter service provision

<u>Evolution of de-icing treatment methods</u>

There has been significant work in anti-icing application methods over recent decades. The developments take place in different ways in different countries and several countries have established test fields and research projects.

To get an overview of the present status of spreading techniques the World Road Association (PIARC) Technical Committee Winter Service has conducted a survey of winter maintenance in the countries it represents. The most important results are described in a report and examples of national studies and experiences are illustrated as best practices [42].

PIARC received 25 completed surveys from 16 countries (12 from Europe, 2 from North America, 2 from Asia). From some countries it received single answers from parts of the country, divided into road types. The participating countries represented different regions of the world and different climatic situations and hence the survey gives a very good overview of the present status and development of winter maintenance practice around the world.

When asked whether it is regularly usual to spread salt in the falling snow during ongoing snowfall nearly 90 percent of respondents answered “yes”. In these cases, brine spreading is not used. Six countries use pre-wetted salt, 12 pre-wetted salt and dry salt, and four use only dry salt. Nine countries also use abrasive spreading materials in some cases - depending on the road type, traffic volume and weather station forecasts, especially the temperature.

In the past, there were discussions about the sense and success of preventive spreading. But the development of new spreading techniques (pre-wetted salt and direct brine application), better road weather information and better experiences in choice of best method and time for application, mean that preventive actions are increasingly used in winter maintenance.

Rising amounts of traffic and the knowledge that accident and congestion risks are very high on icy roads and can be avoided with preventive spreading, have played a strong role in driving this development

Today, more than 80 percent of the participating countries regularly practice preventive spreading . It takes place before frost, black ice and freezing wetness. In nine cases it is also used before snowfall.

Eight countries use pre-wetted salt for preventive actions, seven use only brine; five countries use both, only one country uses dry salt for preventive actions. The spreading rates used for preventive actions are very different (from 5 up to 40 g/m^2), depending on the specific situation. 13 countries have guidelines for preventive spreading rates. All countries report a very positive experience, however, there are no differentiated research results about the influences on salt consumption, cost, traffic flow and traffic safety.

Starting in Europe in the mid-1970s, dry salt spreading was gradually partially replaced by wet salt spreading. Nearly all countries participating in the PIARC survey use this method on all types of roads. In contrast to dry salt, pre-wetted salt avoids significant salt losses due to drifting during application and ensures even distribution and longer adhesion of the salt to the road surface (Figures 22 and 23). Moistening the salt can encourage rapid thawing, especially in dry air.

The usual mixing ratio in pre-wetted salt is 70 percent dry salt to 30 percent brine (“FS30”). The mixture is mixed directly on the spreader immediately before application. The most common brine is sodium chloride solution with a concentration of approximately 22 percent. However, solutions of calcium chloride and magnesium chloride are also possible for pre-wetting salt.

Road salt with anti-caking agents can be used without any further additives. However, some authorities in the UK now use salt with agricultural by-products. These are organic or inorganic substances added to road salt to reduce corrosion and/or improve the spreading properties or surface adhesion of the salt. However, care must be taken to ensure that these additives are biodegradable and not harmful to aquatic life and vegetation.


Figures 22 and 23: Application of 15 g/m^2 salt (fine grained) with a spreading width of 6 m at 50 km/h, left: prewetted salt FS30, right: dry salt.

The spreading of brine only, which was initially tested in Scandinavia [41], is now spreading throughout Europe as another technology for combating slippery roads in winter alongside dry salt and pre-wetted salt technologies. Brine gritting (“direct brine application”, “FS100”) has proven to be the optimal solution for preventive winter service. This technology is an ideal complement to curative winter service with dry salt and pre-wetted salt. Brine spreading offers several advantages that can be used for modern winter service [42].

The advantages of brine spreading over pre-wetted salt are:

- Salt savings (less brine loss due to traffic)
- Greater surface coverage, thus greater effectiveness and increased road safety
- Application at higher speeds possible
- Application is possible the evening before the expected ice event

Figure 24 shows the typical residence time of the salt on the road after spreading for the FS30 and FS100 spreading technologies.

The disadvantages of brine spreading are:

- This technology is only applicable down to road temperatures of approximately -6 °C
- It can only be used when there is little water on the road, e.g., for frost

Typical spreading rates recommended for combating slippery roads caused by frost at a road temperature of -6 °C are 10 g/m² of pre-wetted salt or, alternatively, 20 g/m² of brine. This corresponds to a salt saving of 42 percent (see Figure 25).

The achievable salt savings depend on a variety of factors in each individual case - including traffic volume, the type of road surface, and humidity.

The importance of direct brine application is now recognised in European countries where winter service is necessary, and projects have been initiated to implement this technology in winter service units.

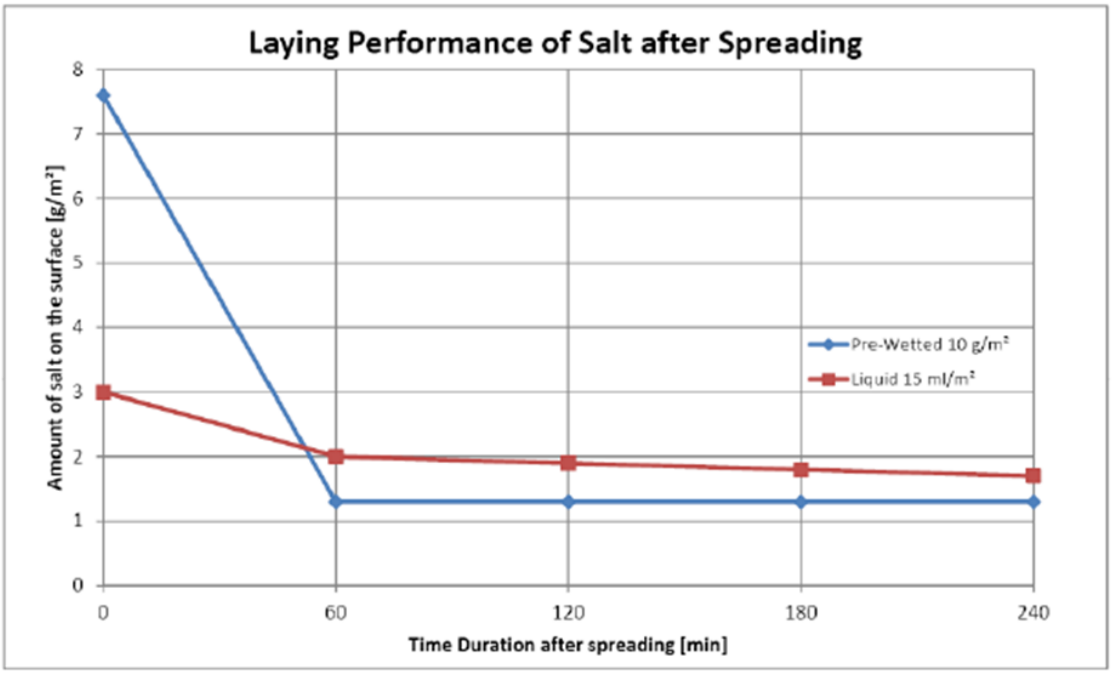


Figure 24: Comparison the laying performance of pre-wetted salt and brine spreading (example from Germany) [42].

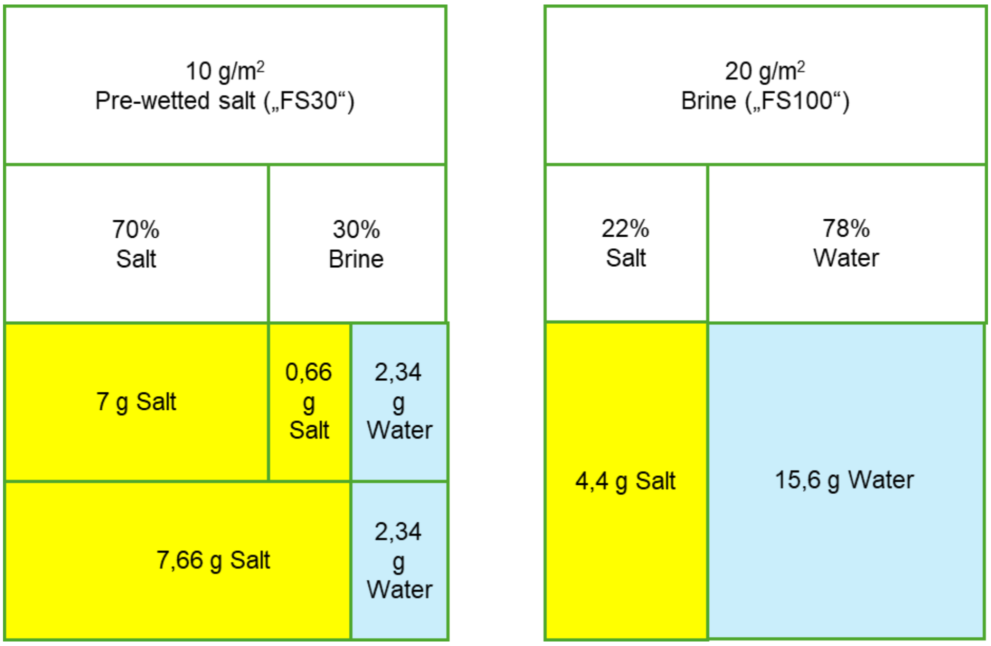


Figure 25: Comparison of the salt quantities applied using the pre-wetted salt and direct brine application technologies against expected frost on a road surface with a temperature of -6 °C.

Cycle paths

It is increasingly recognised that brine spreading on cycle paths is much more suitable than the use of abrasives. With brine applied preventively, cycle paths can usually be used even in winter. On ice days the brine distribution can reach its limits; then the slipperiness is combated with pre-wetted salt. This is shown by examples from Germany: The city of Hanover successfully uses brine spreading on cycle paths. After an initial loss of grip when using magnesium chloride solution, they switched to self-made sodium chloride brine [43]. Until now, the city of Munich had used grit, not salt, on cycle paths when it snowed, out of concern for trees and green spaces. But there were always complaints - grit has a limited grip, and cyclists often slip on rolled gravel. The city is now trying out the use of pre-wetted salt and brine on 10 pilot routes [44].

Resources

Basic requirements for the ability to use brine spreading technologies (FS30, FS100) are:

- Availability of brine in the maintenance workshop

The required brine can be purchased from suppliers or produced in-house in dissolving plants. In-house production is favoured due to its greater availability. Furthermore, when procuring brine on the market, a significant amount of water must be transported by truck: a full tanker truck with 24 tons of ready-to-use brine contains only approximately 5 tons of salt, the rest being water. Purchasing brine from a third party only makes sense if the production facility is located within a short distance from the maintenance workshop.

Typically, a single brine generator with a capacity of, for example, 3 m^3/h, supplemented by brine tanks with a storage capacity of at least 60 m^3, is sufficient for the brine technologies in a master's shop. Brine-only technology requires more powerful pumps to fill the spreaders. Standard requirements for filling capacities (EN 15597-1, EN 17443) apply depending on the tank size on the spreader vehicles (Figure 26).

Figure 26: Configuration of brine production with salt hopper, salt saturator, discharge of insolubles, brine tank, brine loading

In principle, all de-icing salts (rock salt, sea salt, and evaporated salt) are suitable for brine production. However, salts with a high proportion of secondary components (clay, anhydrite) have the disadvantage that these must be regularly removed and disposed of as dissolving residues from the brine generator. When assessing the economic viability of in-house brine production, it must be taken into account that brine salts containing no or very low insoluble components and may have a higher purchase price

It is important to note that sufficient water must be available for self-producing brine. The water requirement depends on the brine production capacity. To produce 1,000 litres of brine per hour with a concentration of 22 percent, requires 256 kg of salt and 909 litres of water. Higher brine production volumes require correspondingly more salt and water.

- Equipping the maintenance workshop with suitable spreading machines

Hybrid spreaders (combi spreaders) are considered particularly suitable for modern winter maintenance. They can apply both FS30 and FS100 salt for preventative and curative applications without the need for conversion. Of course, they can also apply dry salt.

Combi spreaders are also suitable for working on different road widths. This flexibility allows the winter maintenance driver to adapt the spreading method to the road and weather conditions without having to return to the maintenance shop to change the vehicle or spreader.

Combi spreaders can use the spreading disc for direct brine applications with spreading widths of up to 8 m; at this spreading width, it is equivalent to nozzle systems. For spreading widths of up to 12 m on highways, rigidly mounted nozzles or rotating spray units are used. The advantage of nozzle technology is that it allows asymmetric spreading. Vehicles with rotating spray units can only drive in the centre of the road when operating at 12 m. The advantages of spreading discs and rotating spray units over nozzle systems are easier maintenance and the reduced risk of soiling cars and pedestrians (Figures 27 to 30).

Figure 27: Combi spreader with spreading disc for direct brine applications on roadways up to 8 m wide

Figure 28: Combi spreader with rotating spray unit below the spreading disc for direct brine applications on roadways up to 12 m wide

Figure 29: Combi spreader with spray nozzles for direct brine applications on roadways up to 12 m wide

Figure 30: Direct brine application with combi spreaders (left: with spray nozzles, right: with rotating spray unit)

In treating large areas/long routes with brine, spreader vehicles that only carry a large brine tank can also be used (Figure 31).

Figure 31: Direct brine application with a “Full wet” spreading machine

In addition to the liquid-only spreading machines, hybrid spreading machines have proven to be particularly advantageous. These machines can apply both pre-wetted salt and alternatively brine only, depending on road conditions and weather forecast [4,42,45]. A winter maintenance depot should have at least one brine spreader for preventive operations. Depending on the area/route to be serviced, several brine spreaders may be useful.

- Accurate information on weather conditions and trends, as well as road conditions

The availability of a road condition and weather information system (RWIS) is extremely important for maintenance departments to use brine-only technology effectively. The widespread use of RWIS enables targeted, preventative winter maintenance operations.

- Comprehensive training to impart knowledge of brine technology to all employees involved.

In order to spread the use of brine-only technology, it is important to train the purchasers of spreading machines and salt dissolving systems and the road maintenance depot staff. Training should cover the following topics:

- Definition of direct brine application
- Advantages of direct brine application over other spreading technologies
- Technical requirements
- Application and limitations (icy conditions, temperatures, spreading densities, timing of use, circulation times)
- Adjustment of spreading machines
- Cleaning of spray nozzles, spray discs, brine filters, and brine tanks
- Documentation of applications

Economy

While pre-wetted salt offers many advantages over dry salt, it also has the disadvantage of higher investment costs for the pre-wetted salt system in the spreading machine (brine tank and pre-wetting device on the spreading disc), as well as for the production and storage of salt solution in the depot. However, the necessary investments in pre-wetted salt technology pay for themselves in the long term through salt savings.

In a study involving 220 German winter service depots, the practical annual salt savings achieved with pre-wetted salt spreading were determined to be between 24 percent and 44 percent [46]. Cost and return benefit calculations show that, despite increased investment, pre-wetted salt spreading is also economically profitable, meaning that it leads to savings in some cases (Table 3). The greatest impact of pre-wetted salt technology is on the environment: chloride input into waterways and soils is significantly reduced.

Table 3: Example of a comparison of the annual spreading material costs of a road maintenance depot for dry salt technology and wet salt technology

	Dry salt technology	Pre-wetted salt technology
Assumptions		
Consumption of dry salt (t/year)	1,500	900
Produced and used brine (t/year)	-	385
Consumption of dry salt for brine production (t/year)	-	85
Price of salt (€/t)	50	50
Price of brine salt (€)	-	75
Investment costs for brine saturator, brine tanks, and additional costs for spreading machine (€)	-	200,000
Annual variable costs (€)		
Salt	75,000	51,375
Water for brine production	-	700
Electricity for brine production	-	250
Staff for brine production	-	1,000
Annual fixed costs (€)	-	
Depreciation (20 years)	-	10,000

Return on capital (5%)	-	5,000
Maintenance and service (2% investment)		4,000
Annual total costs (€)	**75,000**	**72,325**

The application of the FS100 technology requires, in particular, new technology for brine applications. The technology for brine production is often already available for FS30 technology. In principle, it can be stated that the necessary investment in new spreaders will be covered by the savings in spreading material.

The salt cost savings depend on: the number of preventive applications using direct brine application, the spreading area, and the salt price. When calculating brine costs, it can be assumed that the brine is produced in-house. Fixed costs are not considered, as the salt dissolving systems are already part of the master workshops or are required for the FS30 technology. For example, with 50 preventive full-scale operations against frost down to -3 °C and -6 °C road temperature and a spreading area of 1.0 million m^2, the salt cost savings for FS100 compared to FS30 are 36 percent and 15 percent respectively (Table 4).

Table 4: Examples for spreading material savings from the use of direct brine applications instead of pre-wetted salt on a spreading area of 1.0 million m^2 and 50 preventive applications against frost down to -3 °C and -6 °C

50 preventive applications on an area of 1.0 mio. m^2		
	-3°C	**-6°C**
Consumption of dry salt for FS30 (t)	350	350
Consumption of brine for FS30 (t)	150	150
Consumption of brine for FS100 (t)	750	1,000
Salt price (€/t)	65	65
Cost of dry salt (€)	22,750	22,750
Variable brine costs for FS30 (€)	3,300	3,300
Total spreading material cost for FS30 (€)	26,050	26,050
Variable brine costs FS100 (€)[1]	16,500	22,000
Spreading material savings (€)	9,450	4,050
Spreading material savings (%)	36	15
[1]Specific variable brine costs (salt, water, electricity, staff, disposal): 22 €/t (Salt price: 65 €/t); Dosage FS30 10 g/m^2, FS100 15 g/m^2 (-3 °C), 20 g/m^2 (-6 °C).		

Preventive brine spreading can be carried out the evening before due to its long-lasting properties on the road. Inspection trips are unnecessary. The operations do not have to be carried out shortly before the expected frost event (usually in the early morning hours), as is the case with FS30. This means less night work and reduced personnel requirements. The financial savings for a maintenance depot amount to at least €10,000 over a winter period. The employees are available the next day for other necessary work, such as care of wood along roads and pothole removal. This represents a significant increase in productivity for the maintenance depot.

With the achievable savings in spreading material costs and personnel deployment, the additional costs for combination spreaders can be quickly amortised.

Total environmental impact

- Energy consumption and carbon emissions

It is particularly noteworthy that direct brine application also contributes to the decarbonisation of winter services. The saving of salt through brine technologies is associated with a reduction in energy consumption and the corresponding CO_2 emissions during salt production and salt transport from the salt factory to the winter maintenance operations.

For the exemplary scenario with 50 preventive salting operations using FS100 instead of FS30 during a winter period, the achievable annual salt savings on German motorways amount to 65,000 t. This currently corresponds to a 2,243 t reduction in CO_2 emissions.

The CO_2 emissions attributable to the electricity consumption for on-site brine production and loading can be overlooked, as it is very low. The reduction in CO_2 emissions through direct brine application is expected to decrease in the future due to the increasing decarbonisation of salt production in Europe,

- Water usage

Drinking water from the water utility network, water from private wells, river water, collected rainwater (which may also contain salt), and saline water from industrial processes are generally suitable for brine production. Drinking water quality is not mandatory for brine production. To conserve drinking water resources, the use of drinking water for brine production should be avoided if possible.

If saline industrial wastewater is to be used as a basis for the production of winter maintenance brine, its suitability must be thoroughly tested beforehand, and any necessary treatment steps must be determined. By using this wastewater, discharges into natural waters or sewage treatment plants can be avoided. The use of this wastewater contributes to salt saving and increases ecological sustainability.

- Waste generation

Depending on the purity of the brine salt, residues may be generated during brine production. These are naturally occurring salt by-components, particularly clay materials and anhydrite (calcium sulfate).

These are not hazardous wastes that require disposal in special landfills.

Impact of climate change

Climate change is expected to bring warmer winters and more precipitation. However, more of this precipitation is expected to fall as rain rather than snow. For winter services, this means that ice that occurs at higher temperatures can be combated preferentially with direct brine application. However, it is imperative that sufficient snow clearing equipment and salt stocks continue to be available for heavy snowfalls.

The example of NSNW in Switzerland shows the high extent to which brine application is already possible today. Practical experience shows that direct brine application makes it possible to increase the amount of brine used in a mild winter period to more than 100 percent of the amount of solid salt still required (see NSNW example in section 3).

The city of Berlin has also already achieved a ratio of 60 percent dry salt to 40 percent brine for the mild winter of 2024/25; the brine was applied either as pre-wetted salt (FS30) or without any solid salt content.

An example of widespread brine use in a southern European country is Spain. In the 2021-2022 winter road campaign for the network maintained by the General Directorate of Roads, total de-icer consumption amounted to 101,995 tons of sodium chloride, 133,992 m³ of brine and 93 tons of calcium chloride. Of the total amount, 67,490 tons of sodium chloride (66%) and 128,754 m³ of brine were used in preventive treatments to combat ice [47].

Snowplough with brine injection system

A snowplough with a brine injection system has recently been developed. It has the same features as a traditional plough, plus an integrated anti-ice brine injection system.

During the clearing tour, the brine is directed to the nozzles integrated into the plough blade from a distributor fed by a brine sprayer, a hybrid spreader or simply from a tank mounted on the truck. Unlike traditional snowploughs, which leave a thin, compacted layer of snow on the road surface, the combination of mechanical scraping and application of anti-ice brine is intended to cause the snow to melt immediately, leaving the surface completely clean and already treated with antifreeze [48].

Intelligent Salting Control Optimisation System (ISCOS)

- Automation – across patrol vehicles, loaders, spreaders and command centres – is set to play an increasing role in the delivery of winter service
- New machinery and systems that provide real-time weather data are affording more accurate provision while also improving accuracy, efficiency and safety
- Systems and machines that assess the weather, road situation and service provision necessary are set to reduce the amount of de-icer, spreading and manpower involved in winter service in the years to come.

NEXCO EAST (Japan) developed ISCOS, which automatically optimises and quantifies each operation by linking a tire sensor (CAIS) that automatically detects the road surface conditions with an automatic salting control device for de-icer application.

ISCOS consists of four systems: CAIS (winter road patrol vehicle), supplementary system (winter road patrol vehicle and regional command control desk), optimum amount de-icer loader (DD hopper) and automatic de-icer spreading system (de-icer spreader).

Since ISCOS equips the spreading system based on the surface condition of each 100-metre section instead of the conventional way of deciding application for each several-kilometre section, the n amount of de-icer applied has been reduced by approximately 7 percent, resulting in improved durability of structures and reduced impact on the surrounding environment.

With its automatised surface condition judgement and machine operations, ISCOS has had a diverse impact in improving the accuracy, efficiency and safety of snow and ice control works - from the use of workers and operators without a wealth of experience, to improved work accuracy and reduced workload [42].

Spreading machine with integrated real-time road weather data

Bucher Industries selected Vaisala Mobile Detector MD30 for its ability to collect highly accurate, real-time data on water, ice, and snow layer thickness and road temperature, along with grip, road state, air temperature and humidity. MD30 attaches to any vehicle including snowploughs, where it stands up to slush and constant vibrations. It monitors road conditions and continuously transmits highly accurate data — keeping winter road maintenance operations running smoothly and safely. In a key pilot of MD30 integrated with Bucher Assist, Bucher conducted extensive testing over a full winter season with a winter maintenance organisation in northern Italy which has 13 different terrain areas spread over 27 kilometres. They attached MD30 to a bus for daily detection and on a patrol car for night detection. MD30 registered data every two seconds, which Bucher Assist utilised along with a patented algorithm to calculate the right dosage of solid and liquid treatment for the specific location. Bucher Assist defined the right working parameters for each area and delivered the information to the spreader truck every five minutes. The results of the pilot were astonishing: Bucher Assist, integrated with real-time road weather data, reduced salt consumption by an average of 53 percent in one winter [49].

Floating Car Data (FCD)

Data becomes more and more important in driving forward the development of winter maintenance and finding more efficient ways of doing things. That's why in the winters of 2019/20 and 2020/21 Rijkswaterstaat (Netherlands) worked with NIRA Dynamics to explore floating car data. The purpose was to evaluate what kind of value can be gained from this new source of data in terms of road safety, environmental impact and operation efficiency. This was the world's first large scale implementation and is still at the forefront of using FCD for operations.

As shown in the last evaluation scenario, the friction data especially has undeniable value for winter maintenance. If the winter coordinator would have known the decrease in friction on certain parts of the network he could have altered the routes (fixed or not) to guide the first of the spreaders to the problem areas. Having automated spreaders helps enormously as the coordinator can simply tell the drivers what route to load in the system and start driving.

While there are many opportunities, there is also a risk of over informing the winter coordinators assigned to make the decisions. Data should be delivered in a smart format and in a way that the winter coordinators can work with. A smart dashboard is probably the way forward [50].

IoT

In May 2024, the Fraunhofer Institute IOSB-INA and other partners started the 3-year NachWinD research project dedicated to the challenge of winter service optimisation with digital support and the extent to which the combination of geoinformation, weather data and IoT sensor measurements offers the potential to carry out more targeted and precise clearing and spreading operations. If the deployment decision for winter service, the operations themselves and the follow-up are intelligently supported, this can increase traffic safety on the one hand and reduce resource consumption and environmental impact on the other.

The NachWinD project ("Increase sustainability and precision in winter service"), takes a holistic view of the winter service process and aims to show how, on a local level, fine-resolution real-time data and digitally available expert knowledge about the current road condition, combined with online access to planning data, e.g. predefined waypoints or special restrictions, can enable more precise automatic dosing of road salt.

As part of the project, a user-friendly and learning IoT system is to be built and evaluated to digitally support winter service preparation, implementation and follow-up. So far, winter service has mainly used individual technical systems, often separately from one another. The expert knowledge lies with the long-standing employees and helps them with deployment decisions and winter service implementation. The project aims to bring together technical and organisational individual solutions (IoT, sensors, expert knowledge, regulations, users) into a coordinated overall system (technology/digitalisation and organisation/process/people).

By digitising and modelling expert knowledge, the IoT system is set up as a learning system and is intended to increase the precision of winter service so that the number of gritting/clearing trips is reduced by 10 percent and, if possible, salt consumption by 15 percent. Sustainability in winter service and road traffic safety should be harmonised. The IoT system will be developed with real users and implemented in two real pilot areas in rural and urban environments [51].

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