A Guide to Road Weather Information Systems

Version 2 (August, 2006)

Prepared by:
Steve P. White, John E. Thornes and Lee Chapman
University of Birmingham, UK.
A Guide to Road Weather Systems

1 Introduction .................................................................................................................. 3

2 The Basics of Road Weather .......................................................................................... 4
  2.1 The Need for Road Weather Systems ........................................................................ 4
  2.2 The Importance for Transportation ........................................................................... 4
  2.3 The Consequences and Benefits .............................................................................. 4
      2.3.1 Safety Considerations ....................................................................................... 4
      2.3.2 Environmental Considerations ......................................................................... 4
      2.3.3 Economic Considerations ................................................................................. 6

3 The Road ......................................................................................................................... 8
  3.1 Factors that influence road condition ......................................................................... 8
      Meteorological Parameters ....................................................................................... 9
      3.1.2 Geographical Parameters ............................................................................... 10
      3.1.3 Road Construction ......................................................................................... 14
      3.1.4 Traffic ............................................................................................................. 15
  3.2 Understanding Road Adhesion ....................................................................................... 16
     3.2.1 Road Conditions ............................................................................................ 17
     3.2.2 Levels of Service ............................................................................................. 20
  3.3 Ice, Snow & Avalanche Control .................................................................................... 22
  3.4 Road Salting .................................................................................................................. 26
     3.4.1 Treatment Types ............................................................................................... 26
     3.4.2 Storage Facilities ............................................................................................... 26
     3.4.3 Factors Affecting De-icing Action ...................................................................... 28
     3.4.4 Chemicals Used ................................................................................................. 32
     3.4.5 Surface Type ..................................................................................................... 35
     3.4.6 Spreading Vehicles ........................................................................................... 36
     3.4.7 Spreading Controls ............................................................................................ 36
     3.4.8 Spread Patterns ................................................................................................ 37
     3.4.9 Calibration and Maintenance ............................................................................ 37
     3.4.10 Pre-wetting ..................................................................................................... 38
     3.4.11 Liquid Chemicals ............................................................................................ 39
     3.4.12 Zero Velocity Spreading .................................................................................. 39
     3.4.13 Future Developments ...................................................................................... 40
  3.5 Snow Removal ................................................................................................................ 41
     3.5.1 Removal Vehicles .............................................................................................. 42
     3.5.2 Plough and Blade Design .................................................................................. 43
     3.5.3 Visibility Issues ................................................................................................. 46
     3.5.4 High Speed Ploughing ...................................................................................... 46
     3.5.5 Chemical Ploughing ......................................................................................... 46
     3.5.6 Calibration and Maintenance ............................................................................ 46
  3.6 Friction Enhancement .................................................................................................... 47
  3.7 Automated Spreading Methods .................................................................................... 47
  3.8 Road Heating ................................................................................................................. 48
  3.9 Maintenance Requirements ........................................................................................... 49

4 The Weather ..................................................................................................................... 51
  4.1 Climatology, Weather Conditions & Weather Changes ................................................. 51
  4.2 Road Weather Forecasting ............................................................................................ 52
     4.2.1 Road Weather Models ....................................................................................... 52
     4.2.2 Road Temperature Forecast Curve .................................................................... 54
     4.2.3 The Decision Making Process ............................................................................ 54
5 Road Weather Information Systems (RWIS) ........................................ 55
  5.1 Historical Developments .................................................................. 55
  5.2 Sensors and Equipment ..................................................................... 57
    5.2.1 Outstation Structure .................................................................. 58
    5.2.2 Passive, Active & Remote Sensors .............................................. 60
    5.2.3 Mobile Sensors ......................................................................... 60
    5.2.4 Measurement Methods ............................................................... 61
  5.3 The Role of Road Weather Outstations ............................................ 62
    5.3.1 Maintenance Requirements ......................................................... 64
    5.3.2 Locating Outstations ................................................................. 64
    5.3.3 Deployment Strategies ............................................................... 65
    5.3.4 Trouble Spots .......................................................................... 65
    5.3.5 Micro-climate Representation .................................................... 65
    5.3.6 Virtual Outstations ................................................................. 65
  5.4 Thermal Mapping ............................................................................... 66
  5.5 Thermal Geomatic Surveying ............................................................ 69
  5.6 The Role of the Sky-View Factor ....................................................... 70
  5.7 Data Presentation and Interpretation .................................................. 71
    5.7.1 Winter Maintenance Management Systems ............................... 72
    5.7.2 The Role of Geographical Information Systems (GIS) ............... 72
    5.7.3 The Role of the Internet ............................................................ 72
    5.7.4 The Role of Global Positioning Systems (GPS) .......................... 72
  5.8 International Standards ..................................................................... 73
  5.9 International Approaches & Systems ............................................... 73
  5.10 Information Provision For End Users ............................................... 73
  5.11 Networking and Data Sharing ......................................................... 73
  5.12 The Next Generation RWIS ............................................................ 74
  5.13 Extension to the Footway ............................................................... 75

6 Bibliography ......................................................................................... 76
  6.1 Key References ................................................................................. 76
1 Introduction

Road travel has become an essential component of daily life for many people throughout the world. People expect to get themselves and their ‘goods’ from A to B in the same time throughout the year whatever the weather. The presence of adverse weather conditions, most notably during the winter, has a dramatic effect on road safety and delays. The winter climate in many countries necessitates significant investment for the prediction and subsequent prevention of snow and ice formation on highways, so that users can travel safely and with minimum disruption.

The total annual global expenditure on the winter maintenance of roads is about €10 billion ($10 billion or £6 billion). The benefits of winter maintenance have been estimated to be about eight times the cost. Hence for every €1 spent on winter maintenance approximately €8 are saved (€4 on reduced delays; €3 on reduced accidents and €1 to keep emergency services functional). The costs and benefits of winter maintenance for each country is different depending upon the type and severity of winter climate and traffic volume which will determine the level of investment in depots, salt, vehicles and staff. The weather will determine operational costs of an individual day/night’s treatment. At one extreme is that of snowy environments such as Japan and the cold continental interiors, whilst marginal winter environments where the air temperature commonly fluctuates around freezing point, as in the UK, represent the other end of the spectrum. Between these extremes of climate, a balance of snow and ice hazard exists such as that experienced in Scandinavia. The full range of climates is evident across North America and Europe where approximately 40% each of global annual winter road maintenance is spent. Japan and the rest of the world account for the remaining 20%.

By definition Road Weather Systems are concerned with the interaction between the road and weather, and this guide will consider each of these constituent elements. The guide will then concentrate on the equipment, methods and techniques that have been developed, and continue to be advanced, in the task of managing the highways through the prediction, prevention and removal of snow and ice. Such management systems, which provide operating authorities with helpful information in the decision making process of what action to take, have been termed Road Weather Information Systems (RWIS). Such RWIS comprise a combination of technologies that use historic and current weather data to develop road and weather information that aids decision making. It is intended that this guide will provide a reference source to help understand concepts and the constituent parts of a RWIS, as well as discussing ideas and developments taking place that will play their part in future highway meteorology.

Each highway authority has a different transport infrastructure to manage and no two areas face exactly the same weather conditions. Each authority has a different mix of people and equipment at their disposal, and levels of service will differ between regions and countries. As such winter maintenance strategies are likely to vary to meet specific local challenges, whilst at the same time making as much use of the benefits available from a RWIS.

A European Standard for RWIS “Winter maintenance equipment – Road weather information systems – Product description and performance” (CEN7TC 337 WI 00337006) has been established and is currently in consultation. In North America the NTCIP 1204 (National Transportation Communications for ITS Protocol Environmental Sensor Station Interface Standard – Version 02) suggests standards for RWIS sensors that are close to approval.
2 The Basics of Road Weather

2.1 The Need for Road Weather Systems

The research undertaken to understand the interface between the road and weather, and the solutions developed and implemented throughout the world, are intended to help make highways and pavements as safe as possible for the user whilst taking into account such aspects as safety, environmental and economic considerations.

Around the globe approximately €10 billion is spent every winter in a bid to keep roads open and safe for motorists, cyclists and pedestrians. This involves both the prediction of adverse weather conditions and action taken to prevent ice formation and snow build up, and the removal of ice and snow when it does remain on highways.

2.2 The Importance for Transportation

It is self evident from the extent to which many countries, their economies and social structure rely on being able to move themselves and goods on the highways that the continued availability of the road network throughout the year is of significant importance. The commercial transport industry relies heavily on the continued use of the highways throughout the year. The effectiveness of the haulage industry now allows for just-in-time delivery in many businesses and markets, and which without clear roads throughout the year would result in cessation of plant operations. Public transportation such as bus, taxi and emergency services rely on clear roads year round, as do the travelling public in their own vehicles for whom many rely on the road network to reach places of work and relaxation. Without an understanding and management of the road weather interface and the presence of information systems to help identify appropriate action to take, the cost both financially and socially would be much higher, and result in significantly more accidents and delays on the roads during winter.

2.3 The Consequences and Benefits

2.3.1 Safety Considerations

A considerable number of road traffic accidents can be directly attributed to skidding caused by unfavourable weather. Figures show that the skidding rate for vehicles travelling in icy conditions is double that of wet conditions, which in turn is double the rate for dry conditions.

Despite the increased risk of accidents, fatal injuries are actually reduced during snow and ice conditions as a result of vehicles bouncing off each other as well as drivers compensating for the conditions by driving more slowly. However, these figures do not show the increased occurrence of minor accidents in poor weather conditions and the economic consequences of increased journey times.

2.3.2 Environmental Considerations

To make roads passable in the winter, highway authorities around the world apply chemical de-icers to melt ice and snow or spread sand to help provide traction. The most commonly used de-icing chemical is salt (sodium chloride), which usually comes from mined rock salt that has been crushed, screened and treated with an anti-caking agent (to maintain spreading properties after a prolonged period of storage). The impact of using chemicals for winter road maintenance is a
major environmental concern. Studies show that soils, vegetation, water, highway structures and vehicles are all affected, and so it is crucial that the de-icing chemicals are used wisely.

**Excessive salt usage poses environmental problems by potentially damaging groundwater supplies, soils and ecology.** If there are effects on the environment, they are most likely to occur within 30 metres of the road edge, however traffic and wind can carry road salt and chemicals as far as 50 metres. Beyond this distance salt levels are relatively insignificant. The degree of damage from polluted ground water, surface water and soil largely depends on the type and designated use of the receiving water, and on the drainage system used to discharge the runoff. De-icing chemicals are highly soluble and follow any water flow and are easily leached into water courses such as rivers and streams. The turbulent actions of surface waters, for example, effectively blend and dilute many of the chemicals, whereas the absence of these turbulent actions in ground waters renders them more vulnerable to pollution. Undissolved chemicals can percolate through the soil, being taken up by plant roots and entering the water table. In some reported cases, groundwater carrying de-icing chemicals has contaminated wells, but most of these were apparently caused by seepage from poor storage facilities. The slope of the road is an important factor in determining the extent of salt damage on adjacent vegetation; with steeper down sloped areas typically having the highest percentages of salt-exposed trees. Road drainage, traffic levels, intensity and frequency of applications, prevailing winds and weather conditions also affect exposure distances and extents.

![Pathways of salt to the environment (Source Salt SMART)](image-url)
De-icing chemicals can also accelerate deterioration in concrete and steel structures, and new construction methods are playing a part in helping to reduce the impact. The damage is so severe at Spaghetti Junction in Birmingham, UK that salt can no longer be used as a de-icing agent and an alternative chemical – urea - has to be used. The Ontario Ministry of Transportation estimates that about $216 million in damage results to bridge decks from road salt annually (SMART). Vehicle corrosion is also accelerated through the spread of de-icing chemicals, and it is estimated that this is the largest cost impact of chloride based chemicals. Motorists spend millions annually on vehicle corrosion damage and protection measures. In recent years the use of additives, including agricultural by-products e.g. from molasses, have been tested and are now being sold commercially. These have been shown to have a positive economic and environmental effect by reducing corrosion and road surface damage and aiding the free flow of salt as it is spread on to the roads, so that less needs to be spread at any given point.

Sand and other abrasives are applied to the highways to aid traction on snow and ice covered roads, particularly in countries and regions where it is too cold for de-icing chemicals to work. Although sand is the most common abrasive, slag, cinders and ash from power stations are also used. These abrasives can also have a negative environmental impact by clogging storm, drainage and sewage inlets. The materials may, like other de-icing chemicals, be transported into the groundwater system or aquatic habitats. When it is deposited as sediment in the bottom of rivers, streams or ponds it can have a more significant impact than the chemicals used for de-icing purposes. Anti-caking agents such as sodium ferrocyanide and ferric ferrocyanide are used to help prevent salt from clumping and thus help facilitate efficient spreading on the road surface. These chemicals are very stable and have a low toxicity without sunlight. However, exposure to sunlight could conceivably break them down and release cyanide as a by-product. In sufficient concentrations this could be toxic to fish, but the volatile by-product disappears quickly, and is at sufficiently low concentrations by the time it reaches a stream or lake that it is not a major environmental concern (Salt SMART). Many highway authorities are implementing salt best management practices. These seek to find ways to more effectively manage road salt used in winter maintenance and provide the public with the safe and efficient road system they expect, whilst minimising the effects on the environment. The amount of salt used is a function of local policies, practices, road systems, funding constraints and weather conditions. Because of the variability of conditions and road systems across even a single country, salt management initiatives need to be developed and implemented locally by each highway authority.

2.3.3 Economic Considerations

It is apparent that the benefits of seeking to have in place a proactive, rather than purely reactive, system to act with regard to the forecast and prevailing weather conditions is crucial if highways are to be kept open for as long as possible and the users are kept as safe as possible.

In countries with periods of marginal weather during the winter, whereby the road surface temperature fluctuates within a couple of degrees of zero, the use of RWIS offers a way to provide ice prediction and optimise salt usage. Without such a system, or where little emphasis is placed on using any RWIS it’s capacity, roads can be treated up to three or four times a day, at great cost to the road maintenance budget and the environment. In the UK, which experiences marginal winter weather, in excess of £150 million pounds is spent on winter road maintenance each year. In addition to the direct economic costs associated with the winter maintenance program there are further economic benefits through reduced travel times, crash reductions and hence accident claims and those impacts on infrastructure and the environment already discussed.

In the UK it is estimated that about £1250 per km is spent each winter to keeps main roads open and safe. The high costs of salting mean that winter maintenance engineers face a difficult decision of whether to salt or not. Experiments have shown that four times more salt is required
to melt snow and ice then prevent initial formation. Conversely, if salt is spread to soon, traffic and precipitation may remove the chemical from the road.

Since ice is most slippery at 0°C a small error of judgement on the engineers' part can be lethal. Hence, there is a continual need for improvement in winter road maintenance strategy. The largest potential savings to be made in winter maintenance focus upon the prediction of ice formation and snow, and countries prone to icy roads can make significant annual savings by optimising weather forecasts with salt usage and other operational costs.
3 The Road

Factors that influence road condition

The road surface temperature and condition (dry, wet, ice, frost or snow) varies each day and night according to the road construction, local geography, traffic and weather conditions. Generally speaking the road construction and geography are constants, whereas the traffic and weather will vary in a diurnal fashion. The weather will also vary with the synoptic situation, such as the passing of fronts and movement of air masses.

<table>
<thead>
<tr>
<th>Meteorological</th>
<th>Geographical</th>
<th>Road Construction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar radiation</td>
<td>Latitude and Longitude</td>
<td>Depth of construction</td>
</tr>
<tr>
<td>Terrestrial radiation</td>
<td>Altitude</td>
<td>Thermal conductivity</td>
</tr>
<tr>
<td>Air temperature</td>
<td>Topography</td>
<td>Thermal diffusivity</td>
</tr>
<tr>
<td>Cloud cover and type</td>
<td>Screening</td>
<td>Emissivity</td>
</tr>
<tr>
<td>Wind speed</td>
<td>Sky-View Factor</td>
<td>Albedo</td>
</tr>
<tr>
<td>Humidity / dew-point</td>
<td>Landuse</td>
<td>Traffic</td>
</tr>
<tr>
<td>Precipitation</td>
<td>Slope and Aspect</td>
<td></td>
</tr>
</tbody>
</table>

Parameters controlling road surface temperature

Spatial variations in road surface temperature (RST) around a road network are caused by the interaction of meteorological, geographical, road construction and traffic parameters. On marginal nights, while some sections of road fall below freezing, the rest of a road network may remain well above zero.

Thermally mapped RST data are initially displayed graphically as a pattern of temperature variations along a set route on a given night. Such graphs are called thermal fingerprints, where the amplitude of the thermal fingerprint displays the departure of RST from an averaged value against distance for each route. The amplitude of the thermal fingerprint is dependent upon the weather conditions in the day preceding and during the mapping run. During clear and calm nights (stable conditions) the variations in RST are much more apparent then under cloudy or windy conditions (unstable). Of all the geographical parameters, the sky-view factor has been shown to be the most dominant control on RST but altitude, topography, landuse, road construction and traffic all have significant influence. Road weather models have been continually refined to include a spatial component to incorporate the influence of both meteorological and geographical parameters. However, traffic has so far been a challenging parameter for inclusion in such models.

Information from a variety of sources is needed to help make sensible salting decisions; from weather forecasts, weather radar data, satellite data, local road conditions, sensor data from the immediate area and road surface temperatures. It is the purpose of a RWIS to assimilate the influence of these factors to develop a picture of how RST will vary around a road network in order to aid predictions of when and where freezing conditions will occur.
**Meteorological Parameters**

RWIS monitor substantial quantities of meteorological data. Meteorological parameters are used as a standard input for a numerical road weather forecast to predict RST and road conditions. Such is the influence of these parameters that much of the error encountered when numerically predicting RST is attributed to error in the meteorological input.

Retrospective RWIS data and sensitivity analyses has been used to test the sensitivity of individual meteorological parameters under different weather conditions. Air temperature is the most influential parameter controlling RST and cloud cover, cloud type and wind-speed are very influential upon RST.

Cloud is extremely spatio-temporally variable, making it very difficult to parameterise successfully and is generally accepted as the main source of error during the numerical modelling of RST. Model sensitivity to variations in wind-speed is notable, although not as significant as the effects of cloud cover. Wind reduces radiative cooling by promoting turbulent mixing and thus increases nocturnal RST. Varying the dew-point makes little difference, but this parameter is crucial as a control on hoar-frost formation at the road surface.

<table>
<thead>
<tr>
<th>Type of Slipperiness</th>
<th>Precipitation</th>
<th>Variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precipitation on a frozen road surface</td>
<td>Rain</td>
<td>$T_{\text{air}} &lt; 0^\circ C$ preceding the event</td>
</tr>
<tr>
<td>Snowfall on a frozen road surface</td>
<td>Snow</td>
<td>$T_{\text{air}} &lt; 0^\circ C$</td>
</tr>
<tr>
<td>Snowfall on an unfrozen road surface</td>
<td>Snow</td>
<td>$T_{\text{air}} &gt; 0^\circ C$</td>
</tr>
<tr>
<td>Snowfall with hoar-frost</td>
<td>Snow</td>
<td>$T_{\text{air}} &lt; T_{\text{dew}} &lt; 0^\circ C$</td>
</tr>
<tr>
<td>Hoar-frost with low visibility</td>
<td>No</td>
<td>$T_{\text{air}} &lt; T_{\text{dew}} &lt; 0^\circ C$</td>
</tr>
<tr>
<td>Freezing dew followed by hoar-frost</td>
<td>No</td>
<td>$T_{\text{air}} &lt; T_{\text{dew}} &lt; 0^\circ C$</td>
</tr>
<tr>
<td>Strong formation of hoar-frost</td>
<td>No</td>
<td>$T_{\text{air}} &lt; T_{\text{dew}} &lt; 0^\circ C$ &amp; Wind $&gt; V_c$</td>
</tr>
<tr>
<td>Weak formation of hoar-frost</td>
<td>No</td>
<td>$T_{\text{air}} &lt; T_{\text{dew}} &lt; 0^\circ C$ &amp; Wind $&lt; V_c$</td>
</tr>
<tr>
<td>Drifting snow</td>
<td>Snow</td>
<td>Various with wind</td>
</tr>
<tr>
<td>Watercover which freezes</td>
<td>Rain</td>
<td>$T_{\text{air}}$ proceeding the event</td>
</tr>
</tbody>
</table>

**Types of road slipperiness that can be detected from meteorological observations (Univ Goteborg)**

The table above shows that in order for a road to freeze, there needs to be an input of moisture to the road surface. This may be in the form of precipitation either before or during the freezing event or alternatively due to the sublimation of water vapour on the surface which subsequently freezes as hoar-frost. Hoar-frost is formed on roads when the road temperature falls below the dew point temperature and the volume is dependent upon critical values of relative humidity and wind-speed. At high levels of humidity it is not uncommon for hoar-frost to be accompanied with poor visibility, adding a further hazard to the already frozen road. However, one disadvantage of this classification is that it does not account for the hygroscopic nature of salt which is a major control of surface moisture on treated roads. The largest source of winter accidents is precipitation; in particular snow on an already frozen road surface.

The most complicated forecast situations are encountered when the level of atmospheric stability changes over the course of the night. RST responds quickly to changes in weather conditions, particularly the change from clear to cloudy conditions or the reverse.
3.1.2 Geographical Parameters

Latitude and Longitude

Latitude is an important control on climate and RST. For example, Scotland has more snow than other parts of the UK. Countries at higher latitudes have longer winter seasons, but countries as far south as Greece and Spain still have ice problems. Overall, the main influence of latitude is that it determines the maximum amount of incoming solar radiation at any location. To calculate incoming solar radiation the relationship between the earth and the solar beam is modelled geometrically to calculate the position of the sun in the sky hemisphere at any location and for any given time. Longitude is often important in determining the continentality of a region and the distance from the sea.

Altitude

Altitude is a significant cause of temperature variation of a road surface. Temperatures decrease at higher altitudes as a result of the environmental lapse rate, with a maximum of 9.8°C.km\(^{-1}\) but more typically 6.5°C.km\(^{-1}\). In Nevada, USA, altitude has been shown to have a considerable effect on RST, but the relationship with RST is complicated and non-linear. As a parameter, the effects of altitude on RST are most predictable during times of low atmospheric stability.

Variation of mean minimum air temperature with altitude for twelve sensor sites in Herefordshire
Topography

Topography is often considered to be the major factor in causing differences in RST during extreme nights, with small differences in topography producing considerable variations in air temperature and RST across a road network. Variations in temperature induced by topography often cause the lowest RST on a road network to be recorded at valley bottoms – or frost hollows. During stable conditions, a layer of dense cold air forms at the surface causing a temperature inversion. If the topography is undulating, the layer of cold air becomes mobile and gravitates down slope as a katabatic flow.

Cold air flows follow lines of drainage and continue moving until a topographic or thermal barrier is reached. The actual flow can occur quite suddenly and a strong katabatic can develop within half an hour of sunset. Flow then occurs as a series of pulses at harmonics dependent upon the topography and continues until the topographic feature is filled or until sunrise when the phenomenon is rapidly destroyed. At the top of the temperature inversion, lapse rates return to normal and temperatures are at their warmest. This feature is called the thermal belt and is a dynamic feature whose height varies considerably with the strength of the katabatic flow and the relative size of surrounding topography.

Katabatic flows result in lower air temperatures in valley bottoms and hollows than the surrounding topography which, on marginal nights, can lead to radiation frost pockets – white spots. The accumulation of cold air is well studied and statistical relationships have been developed in an attempt to quantify the differences in temperature. More sophisticated techniques have been developed using digital terrain models to produce frost risk maps. The criteria required for katabatic drainage ensures that the impact of topography is greatest under extreme conditions. When wind-speeds exceed 3$m^{-1}$ and/or cloud cover increases any differences between valleys and surrounding areas are virtually eliminated.

In reality, few nights actually have sufficiently low regional wind-speeds for katabatic drainage to take place. Hence, at more moderate velocities the topographic exposure of the valley becomes an important parameter. Topographic features dominate airflow at a local level, with wind-speeds increasing with elevation and exposure. Any variation in air temperature is linearly related to RST, but there is a tendency for minimum RST to be higher than air temperature in the autumn and lower in winter and spring due to the thermal inertia of the road construction.
**Sky-View Factor**

The sky-view factor (SVF) is a dimensionless parameterisation of the quantity of visible sky at a location. Represented as a value between zero and one, it will approach unity in perfectly flat and open terrain, whereas locations with obstructions such as buildings and trees will cause the SVF to become proportionally less becoming zero in a tunnel.

The SVF has a particularly important role in the nocturnal radiation budget. Surface geometry prevents the loss of long-wave radiation from the ground by the replacement of a section of the cold sky hemisphere with a warmer surface. This results in increased air and surface temperatures at locations with low SVF. Heat losses from the surface depends on the conduction of heat through the surface interface, e.g. via deep conduction from the ground or internal heat conduction in buildings. The relationship between SVF and temperature is so strong, that SVF is considered to be the dominant parameter in causing the urban heat island phenomenon discussed later in this section.

Another consequence of SVF is that it can be used to quantify sheltering effects. Buildings and forests will afford a degree of wind shelter similar to that of topography which could possibly lower RST. This theory has been validated at coniferous sites in Sweden where RST differences of up to 3°C have been found between roads in sheltered coniferous forests and exposed areas.

**Screening**

Short-wave radiation from the sun is partitioned into direct and diffuse components depending upon atmospheric attenuation from cloud and pollution. The quota of radiation received at a location is approximately proportional to the amount of direct solar radiation, but the actual geometry of the surface is also influential. If a surface is in shadow, be it from trees, buildings or topography, then direct radiation will not be received. The simple parameterisation obtained with the SVF can also be used to describe the effect of surface geometry on the quantities of incoming radiation at locations with an obstructed sky hemisphere. However the SVF does not detect the distance of the shading objects from the road. The modelling of two components is therefore required:

1. The position of the solar beam in relation to the screening object and the location. Known as a sun-track, the path of the solar beam is different for each day, and is calculated using solar zenith and azimuth angles.
2. The size, shape and orientation of screening factors and proximity to a location. As a result of surface geometry, buildings and trees locally block the solar beam preventing certain sites from receiving the full quota of direct solar radiation at various times of the day, although diffuse components will still arrive. Blocking of the solar beam is analogous to the setting of the sun causing the earlier occurrence of local sunset and subsequent later sunrise at screened locations.
Landuse and the urban heat island

The urban heat island is a consequence of microclimatic changes caused by anthropogenic alterations of urban areas and at night the city can be several degrees warmer than its surroundings. The intensity of urban heat island can be represented as a function of city size, population, land-use and atmospheric stability where intensity is strongest in ‘ideal’ clear and calm conditions. The relationship is strongest in the city centre, but the impact of SVF has been shown to be also detected in suburban areas.

The occurrence of heat islands in cities is a common feature, particularly under stable anticyclonic conditions, the same conditions conducive to low RST and icy roads. If areas such as city centres with low SVF can be shown to be consistently warmer, it is possible that on marginal nights de-icing may not be necessary at these locations. However, due to increased traffic density, cities are in fact often treated more frequently. Every building or intrusion into the cold sky hemisphere is capable of producing its own heat island and even compact villages can have a surprisingly large thermal influence. Hence, there is a need to incorporate this effect into numerical road weather prediction models to improve the prediction of RST.
3.1.2 Road Construction

Highway construction profiles can generally be split into two types, namely concrete profiles and the more common four layer flexible pavements.

The surface layer typically consists of bituminous layers such as asphalt and is sub-divided into a wearing course and a basecourse. However, it is common on low trafficked roads for these two courses to be combined into a single homogenous layer. The roadbase layer consists of cement bound aggregates and represents the thickest layer of a flexible pavement. Finally, the subbase is a simple continuation of the roadbase. This layer is generally more aerated and is often used for drainage. The exact nature of road pavement construction profiles will vary around any road network. Deep profiles will be found on motorways and major roads whereas minor roads only require a shallower construction.

The term ‘thermal memory’ is used to describe the length of time which a surface stores heat from daytime solar radiation. Major roads such as motorways have a large thermal memory due to the deeper pavement construction. This often makes them the warmest sections of a road network. However, if a road crosses a bridge or is more minor, the construction and thermal memory can be greatly reduced. Such reductions are explained by considering how thermal properties change within the road construction profile (see table below).

**Typical values of the thermal properties of road materials**

<table>
<thead>
<tr>
<th>Material</th>
<th>Position</th>
<th>Conductivity (W m⁻¹ K⁻¹)</th>
<th>Heat capacity (10⁶ J m⁻³ K⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asphalt</td>
<td>Wearing course</td>
<td>1.40</td>
<td>2.1</td>
</tr>
<tr>
<td></td>
<td>Basecourse</td>
<td>1.00</td>
<td>2.1</td>
</tr>
<tr>
<td></td>
<td>Roadbase</td>
<td>1.00</td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td>Sub-base</td>
<td>1.25</td>
<td>1.9</td>
</tr>
<tr>
<td></td>
<td>Subsoil</td>
<td>1.30</td>
<td>2.5</td>
</tr>
<tr>
<td>Concrete</td>
<td>Roadbed</td>
<td>2.60</td>
<td>2.4</td>
</tr>
<tr>
<td></td>
<td>Sub-base</td>
<td>1.25</td>
<td>1.9</td>
</tr>
<tr>
<td></td>
<td>Subsoil</td>
<td>1.30</td>
<td>2.5</td>
</tr>
</tbody>
</table>

Thermal conductivity is the ability of a material to conduct heat whereas heat capacity is a measure of how efficiently a material can store that heat. Other variables useful to consider are thermal diffusivity and thermal admittance. Thermal diffusivity is the speed at which a profile adjusts to temperature change whereas thermal admittance parameterises the surface heat budget with respect to the rate heat is absorbed (albedo) and emitted (emissivity). Overall, the effects of thermal properties are more noticeable during early and late winter when the input of solar radiation is greater.

Different road surfaces are visible to the naked eye, and are often more so after precipitation has fallen. Some remain wet after rain has fallen, whilst others quickly dry, some are dark in colour, and after application of salt some have a white dust coating. It is most likely that the dry surfaces are the more traditional, impervious, warmer surfaces.

Porous asphalt surface courses will reduce spray from vehicle wheels, and generally they are quieter. However porous asphalt roads cool more quickly than normal road surfaces and have lower minimum road surface temperatures. Consequently they normally require more frequent salting than normal asphalt roads.
3.1.3 Traffic

In addition to increasing quantities of anthropogenic heat, vehicles promote mixing of warmer and cooler air layers and also prevent long-wave radiation loss from the road surface. The full impact of vehicles can be quantified on multi-laned roads, where an increased volume of slower moving vehicles on nearside lanes can produce temperature differences of up to 2°C. The impact of traffic on RST can be noticed on most nights, but values are greater in clear conditions when large traffic volumes can prevent radiative cooling.

From its development in the 1970s, the accuracy of thermal mapping has been subject to numerous systematic and random errors. One source of error in the prediction of RST is the effect of traffic, which has been shown to have a significant influence on road surface temperatures. Studies in the UK reveal consistent temperature differences of around 1.5°C across the lanes of a dual carriageway road.

There are several ways in which traffic can modify RST. Heat will be added to the road surface via sensible heat and moisture fluxes from the engine and exhaust as well as frictional heat dissipation from the tyres and braking. Vehicles can block long-wave radiation exchange whilst also preventing short-wave radiation from reaching the road surface during the day. The movement of traffic will also cause additional mixing of air above the road surface promoting increased turbulent flow. For example, in a study in the Stockholm area of Sweden, it was shown that during the early morning rush hour, RST can increase by up to 2°C more in urban areas than rural areas. Fortunately, multi-laned roads provide a unique opportunity to attempt to quantify traffic effects. As other geographical parameters and climatological processes can be assumed constant, the actual impact of traffic density on RST can be quantified. Studies conducted in the UK found 1°C and 2°C differences respectively between the inside and outside lanes of a motorway.
Understanding Road Adhesion

Ice forms on the road when:

- Water is present in a liquid form
- The temperature of the water drops below the freezing point

There are a number of sources from which the water can find its way to the road surface, and there is more than one way in which the temperature of water can fall below freezing:

- It can freeze in the atmosphere and land as snow or ice
- It can land as liquid on a cold road and freeze

Individually, none of the following conditions is inherently problematic: moisture on the road; air temperatures below freezing; high air moisture levels; or road surface temperatures below freezing. Yet the combination of two or more could lead to problems that need to be addressed by anti- or de-icing action.

Moisture on the road and surface temperatures below freezing is the most likely combination requiring action. Regardless of the ambient air temperature, if the road surface temperature is below freezing and there is moisture on the surface, ice will form. High air moisture levels along with both air and road surface temperatures below freezing will also cause ice to form. When road temperatures fall below the dew point, moisture will condense on the road surface. If the surface temperature is also below freezing, frost will form which can be compacted into ice by traffic.
Road Conditions

Road conditions obviously vary throughout the year, and during the winter period the four main possibilities are for the road to be dry, wet, with ice or with snow. The air temperature at different vertical elevations determines the type of precipitation that falls, but it is the road surface temperature that has the largest influence on whether or not that moisture will become – or remain – ice or snow. Precipitation falls from the clouds in one of five different forms; rain, freezing rain, sleet, snow and hail – and sometimes a combination of one or more of these forms. The vertical temperature profile is the determining factor as to which form of precipitation arrives at the road surface.

Freezing Rain

Freezing rain is probably the most dangerous form of precipitation, in part because there is no noticeable difference between this and rain. Freezing rain occurs when there is a shallow layer of sub-freezing air at the surface underlying an above-freezing layer of air above it. The precipitation falling through the warmer layer does not freeze. When it enters the sub-freezing layer it is rapidly cooled, but still does not freeze. When it lands on a road surface that is below freezing, the super-cooled water droplets freeze on contact, forming a layer of ice.

An ice covered roads following precipitation

Sleet

Sleet occurs when there is a warm layer of air above a relatively deep sub-freezing layer at the surface. The layer above freezing will allow for liquid precipitation but as the drops enter the cold layer, they will freeze and hit the road surface as frozen water droplets. Sleet in itself does not necessarily cause significant problems on the roads, but the conditions that produce it can quickly change and result in the formation of freezing rain and ice formation.
The atmospheric temperature profile typically associated with sleet

Snow

Snow occurs when the layer of the atmosphere from the surface through the cloud is entirely below freezing. The precipitation falls from the cloud as snow and does not melt while falling to the road surface. Snow that falls on dry roads with below freezing temperatures does not represent an ice problem, although the snow will need to be cleared.

The atmospheric temperature profile associated with snow

A snow covered road following recent snow fall
**Hail**

Hail forms as a by-product of strong updrafts that exist in thunderstorms. The cumulonimbus clouds that are associated with thunderstorms can grow to heights where the temperature is below freezing. Droplets of water will rise up with the upward directed wind as they collide with other droplets and increase in size. This will eventually result in the droplets freezing into a hailstone. When this hailstone grows too large to remain suspended by the updrafts it will fall to the road surface. Although hail is not usually associated with winter storms, extreme events under the right conditions can result in ice formation on road surfaces. In these instances in winter, although less common, it may be necessary to undertake de-icing or even ploughing operations.

**Frost**

Frost forms when the road surface temperature falls below the dew point of the air above the road. Small deposits of frost are rarely dangerous and can be seen by drivers but significant amounts of frost can be compacted into ice by traffic.
Levels of Service

Winter maintenance engineers not only need to know how much salt to apply, when to apply it, and even whether it should be applied, but also where to apply it. It is impossible, both operationally and financially, to treat all roads in a given area, and so a selection must be made as to which roads are treated. Highway authorities seek to achieve pre-determined levels of service based on typical local conditions, climate and needs.

For example, in the UK and Canada, a distinction is made between primary, secondary and even tertiary sections of road. Those roads crucial for emergency services such as access to hospitals as well as main roads fall into the primary category, whilst many rural areas with lower usage are likely to fall into the tertiary category. In the US, most state authorities operate a four service level system for prioritising road treatment similar to that used by the Iowa Department of Transportation of:

- A-level: the Interstate system
- B-level: the Commercial and Industrial network and roads with more than 5,000 vehicles per day
- C-level: roads with more than 2,000 vehicles per day
- D-level: roads with less than 2,000 vehicles per day

Salt Institute, [http://www.saltinstitute.org/los.html](http://www.saltinstitute.org/los.html)

The process of establishing levels of service categories will most often be determined on the basis of traffic volumes, road classification, importance of the road for access e.g. emergency route, lorry route and economic route. It is likely to be a broadly participative process; led by the highway authority and in consultation with emergency services, schools, businesses, home owners and road users in a given region. However, level of service priorities are not always communicated to the travelling public, such that they may have a widely varying perception regarding the service they do and should receive. There are three level of service perspectives that may not always have the same objective:

1. The level of service prescribed by the highway authority
2. The service that is actually delivered by the highway authority / operator
3. The service that the travelling public expects

The ideal situation is when the maintenance services that are provided and those that are expected by the public are the same as the level of service prescribed by the highway authority. Public expectations should be heeded, since where the public expects a higher level of service than prescribed; there will be pressure to increase it. The road network that is covered and the level of service prescribed should be reviewed regularly, particularly as new infrastructure is built and the patterns of road usage change over time.

With the increase in performance based management, it is likely that level of service goals will be established in some countries and regions linked to the stated levels of service. These may be in the form of the timing and frequency of treatments or road conditions after an event e.g. bare surface in a given timeframe. Whatever goals are chosen, they should be meaningful, measurable and achievable. Outcome measures such as these depend on the collection of data and measuring service performance. Developments in the area of RWIS, GIS and GPS to name but a few have led to the capabilities to better monitor and assess levels of service delivered.
A RWIS plays a significant part in helping inform the decisions made, but the highway engineer also needs to understand the chemical behaviour of salt and other chemicals being spread. With a number of vehicles at the operator’s disposal, and a limited time in which to conduct the salting operation, authorities will divide the primary, secondary and tertiary sections of road into a number of routes. This will be done in such a way that a subset of the road network will comprise of primary, secondary and tertiary salting routes that can be completed in a similar time frame. This would mean that in the event of needing to salt, a decision is taken as to whether to salt all primary, secondary etc roads, and once that decision is made all primary routes would be completed in a similar time if they commence at a similar time.

The PIARC (Permanent International Association of Road Congresses) "Snow and Ice Databook" outlines levels of service in a selection of countries around the world.
Ice Control

There are two main approaches towards ice control; known as anti-icing (precautionary or pre-salting) and de-icing. Anti-icing involves the application of chemicals to the road to try to prevent the bond between ice and road surface forming or developing. If a bond does form after an initial anti-icing treatment, it will be weak and should be removed more easily than had no chemicals been spread. This proactive approach is undertaken prior to the ice or snow forming on the road network, and hence is heavily reliant on an accurate RWIS to indicate when and where adverse road conditions are likely to occur. By applying chemicals to the road prior to ice forming it is possible to reduce the volume required, and hence minimise usage whilst maintaining safe passage for motorists. The lower volume of salt and other chemicals applied also has the benefit of minimising harm to the environment and keeping costs low.

The second approach is that of de-icing. By contrast this is an after-the-event action that involves spreading salt or other chemicals onto the road to break the bond of already bonded ice and snow i.e. to melt existing ice and snow. This approach could in the first instance be seen as being purely reactive; waiting until after the precipitation has fallen and settled prior to spreading chemicals to combat the ice and snow. However, that is not the whole picture, and based on the information from a RWIS, the operating authority may decide that it is more appropriate to wait until precipitation has begun to fall before commencing their ice control operations. This occurs when heavy wind and / or rain is forecast, which would be likely to wash away any chemical that was laid prior to the conditions resulting in ice forming.

In both these approaches, the aim is to clear the road to the bare pavement, although this is not always possible. Using the approach of anti-icing, usually with liquid chemicals to improve adhesion to the road surface, typically reduces the total chemical usage and allows a high level of service to the road users. Anti-icing can support a requirement for safe road conditions during a winter storm, whereas the reactive de-icing approach cannot accomplish this. If a sudden and/or unexpected change in the prevailing weather occurs, or there are insufficient personnel or equipment to conduct initial and subsequent anti-icing treatments, there may be no way to prevent the bond from forming. In these instances, de-icing is the only option available to break the bond before mechanical removal of the accumulated precipitation; although this approach will require more time, chemicals and equipment to achieve any given level of service requirement.

Sometimes abrasives are spread to increase traction between vehicles and the ice or snow covered road. There are numerous variables involved in the spreading of anti and de-icing chemicals; the treatment type, the chemical itself, its grade, method of spread, the volume of chemical and rate of spread and characteristics of the surface being spread upon. Some of these factors will be considered in greater detail in following sections.

Rock salt comprises negatively charged chloride ions and positively charged sodium ions, which are bound together to form crystals. As long as these ions remain united they have no effect on ice. In order for salt to melt ice, it must be dissolved in water to form brine, which then has the effect of causing ice to melt. During normal de-icing operations, road salt is applied on top of any ice or snow that lies on the road. If there is sufficient moisture and heat, usually as a result of a combination of solar radiation, traffic and warmer daytime temperatures, the salt dissolves and forms a brine. Due to its greater density than water, brine moves downward through the ice and snow to the road surface.
The role of brine on the road surface can be described in the following stages:

1. Salt is spread on the surface of ice/snow (only for a few cms).
2. The salt draws moisture from the snow or ice and begins to form brine. The salt crystals are now coated with a layer of brine, enabling them to begin augering down to the surface.
3. Due to the action of the brine, the bond between the ice/snow and the road surface begins to weaken as the ice melts. Eventually the bond is broken and the remaining ice/snow floats on the brine layer rather than on the road surface.
4. Traffic breaks through the surface and reduces the remaining ice/snow to slush. Continuing traffic movement moves the slush to the side of the road, and any remaining slush may be cleared by snow ploughs.

The Role of Salt in Ice Removal

The key to more efficient salt usage and safer road conditions is to apply salt at the beginning of a winter storm to create a road condition that will prevent freezing and the formation of the ice-road surface bond. Such a proactive anti-icing approach relies heavily on the ability to forecast prevailing weather conditions and their impact on the road surface, and hence RWIS have a crucial role to play.

Salt is also applied in freezing rain conditions, often along with abrasives, to establish rapid traction and melt the ice. If an anti-icing chemical is applied to a dry road in advance of freezing rain, a liquid solution should be applied. Applying a solid chemical will result in an endothermic reaction that will cause the road surface temperature to fall, and has the potential to exacerbate the freezing rain conditions.

Salt must not be spread on freshly fallen snow of more than a few cms. There are environmental laws in most European countries which forbid this. Snow has to be removed mechanically before any thawing agent is applied.
**Snow Control**

Increasingly an anti-icing approach is being used in areas of snow control. Previously authorities would wait until a predetermined amount of snow had accumulated on the road surface before commencing removal procedures. In addition to ploughing, authorities would apply de-icing chemicals to aid the removal of snow and ice. Such a reactive approach allowed the formation of a compacted layer of snow on the road surface, which becomes tightly bonded under the compaction of traffic and hence requires a large amount of de-icing chemical to penetrate the snow and ice and ultimately break the bond between the frozen material and the road surface.

With accurate forecasting of winter conditions, de-icing chemicals can be applied prior to a snow storm and thus reduce the likelihood of snow or freezing rain to bind to the road surface. It is important to note that snow and ice control do not necessarily function independently and that actions taken in ice control are also used in snow control.

One of the most difficult conditions for highway authorities to deal with is that of drifting snow. Highway authorities need to have an understanding of the likely local effects of high winds and potential trouble spots. As well as knowing where this is likely to occur and the route likely to be taken by the snow, they need to have a plan of how to tackle them. Proactive, preventative measures include the erection of snow fences and the creation of snow windrows to act as windbreaks against drifting. Once the high risk drift areas have been identified, operators can be deployed to erect snow fences in the period leading up to a winter.

*High snow banks can cause numerous hazards*

In some localities, particularly Japan, North America and Canada, a large amount of snow can fall and snow banks grow out of control. They obstruct the line of sight for drivers, encroach on the road reducing lane width and are a hazard to pedestrians trying to cross the road. The most common solution in dealing with deep snow like this is to load it into vehicles and transport it to a snow storage site for disposal. This is in effect trading one set of challenges for another, since when all the snow is moved from urban roads to a disposal site, along with the snow come contaminants that must be contained and disposed of as the snow pile melts. Snow removed from highways often contains chloride, sodium and calcium from salting operations; and it is also likely to contain heavy metals, hydrocarbons, rubber and other debris deposited by vehicles.

The method that works best for snow removal depends on the amount of storage space parallel to or near to the highway. The least expensive method is to dispose of it as close to where it accumulates as possible. However, in urban areas this is not always easy and so a snow blower may be used to transfer snow beyond the area immediately adjacent to the roadside, although care must be taken not to cover the footways which pedestrians will need to use. Sometimes snow banks are even spread back on to the travelled portion of the highway in order to hasten
snow melting. Mobile snow melters are also used in some countries (not in Europe) to melt accumulated snow at the roadside where the meltwater can be disposed of through the storm sewer system. Despite being an expensive solution, this option may be suitable for areas where haul distances would be long or snow disposal site capacity is limited. The ability of the storm sewer system and discharge site to handle the additional capacity and contaminants are important factors to consider before something like this is implemented (Salt SMART). Where no adjacent storage areas are available close to snow banks, the snow is loaded onto vehicles and hauled to disposal sites.

*Mobile snow melter*

**Avalanche Control**

Testing equipment that will automatically close roadways a few seconds after an avalanche starts.

"The goal is not to forecast avalanches, but to detect the onset of avalanches," says Rand Decker, associate professor with the University of Utah's Department of Civil Engineering. Decker says an avalanche's "time of descent," the time it takes it to travel from its point of origin to the roadway below, often is between 30 seconds and a minute.

Invasive sensors -- "geophones" implanted in rock or soil -- can detect avalanches in time to trigger a response such as the closing of railroad crossing gates to prohibit access to the roadway below. Funding for the project comes from DOTs in Idaho, Utah and Wyoming, which already are trying out the system; from the Colorado and Washington DOTs, which eventually plan to implement it; and from the FHWA's Office of Technology Applications.
Road Salting

Treatment Types

Both **anti-icing** (precautionary salting) and **de-icing** involve the dispersal of chemicals onto the road surface, usually from a moving vehicle, to either inhibit the formation of, or melt previously formed ice and snow. The main chemical to be spread is sodium chloride (common salt) and hence the operational task of applying anti and de-icing chemicals to the road is often referred to as salting. Other chemicals are also used in this process, and will be discussed in more detail later. During the months prior to the winter highway authorities seek to ensure that sufficient quantities of chemical are stockpiled and spreading equipment is moved to strategic locations in readiness for use throughout the winter period.

Highway authorities will have different equipment to maintain anti- and de-icing chemicals in required states and conditions. Some chemicals will be delivered to operating depots in the form in which they will be spread; either as solid granules or in liquid form. Other chemicals are more cost effectively converted into liquids from solids delivered by the manufacturer.

The number and length of routes to be treated and the equipment capabilities will greatly influence the location of storage facilities and depots. Weigh bridges are a feature of winter maintenance depots, as vehicles used to spread anti and de-icing chemicals are weighed prior to and after operations. This allows the amount of chemical spread to be calculated, stock levels to be maintained based on usage throughout a season and provide assistance in any necessary auditing processes.

Storage Facilities

Maintenance yards can be the source of significant salt loss to the environment; whether in the form of salt dust, brine run-off or simple wastage through improper handling practices, with lost salt dissolving and infiltrating the soil below and adjacent to the site. Different authorities use varying grades of salt, depending on the dominant needs and equipment set-up of their vehicles. However, once authorities have purchase salt stock, of a given moisture content, they will seek to maintain the quality of this and minimise any local environmental damage. The storage of salt can result in stockpile run-off when exposed to precipitation, and the possibility of contaminating ground or surface water needs to be minimised by covering the salt and storing it on an asphalt or impervious base. Salt is usually stored under cover in salt barns to prevent run-off, maintain the given moisture content of the salt and prevent contamination.

Highway authorities will seek to design and operate the maintenance facilities in such a way as to minimise salt loss through precipitation or wind. They will often erect permanent salt storage facilities, known as barns. At other times temporary structures will be erected using impermeable bituminous bases covered with a waterproof material, such as tarpaulin or polyethylene, to ensure the salt is kept as dry as possible. The floors of the structures should be sloped away from the centre of the storage area for drainage purposes. If asphalt or concrete floors are used, these should be sealed to minimise infiltration. Designs of storage facility range from domes to rectangular sheds to elevated silos. Domes are the most popular design, with an efficient surface area to pile volume ration. Since salt can be lost to precipitation, all designs should be aimed at keeping precipitation out of the salt, or, if that is unsuccessful, containing any salt-laden water that may be created. If salt is to be mixed with sand, then as much as possible of this should be undertaken during the dry summer months and when there is minimal wind to blow it away.
Well designed entrances on storage structures will take into consideration the prevailing winter wind direction to help keep out precipitation. Spillage during stockpiling and vehicle loading is the main source of salt loss (Salt SMART), and so the more these activities are carried out under the cover of a well-designed structure the less salt will be lost to the environment. The loading and unloading of spreading vehicles will be sought to be undertaken indoors where possible to minimise the moisture contact with the chemical. The moisture content affects the mechanical operation of the salting process, sometimes hampering the spread, or the effectiveness of the salt once it is spread on the road, so any changes in this will affect the efficiency of the operation when it comes to be used. It is usually only the drier types that are stored outside, where it will naturally absorb some moisture from the environment prior to spreading.

Salt spreading vehicle exiting from a salt barn
Factors Affecting De-icing Action

Most of the decision-making in winter maintenance involves consideration of multiple factors and variables. Temperature, moisture and time of chemical application are the controlling factors, but also to consider in the process of melting ice and snow are variables such as the chemical used, the quantity used and its effect on phase changes, weather conditions, type of road surface, topography and traffic volume.

Temperature

Temperature is a critical factor in the salt-to-brine process, with the road surface temperature trend being more crucial than the air temperature when deciding on a salting strategy. Normal rock salt comprises sodium chloride (NaCl) crystals held together by an electrolytic bond. Heat is required to break this bond, causing the separate sodium and chloride ions to go into solution. When there isn’t enough heat present in the atmosphere, the road salt will draw it from the nearest available source – which is the road – as it dissolves into brine. Under certain conditions it may be appropriate to apply a heat-producing catalyst such as liquid calcium chloride, which may be especially beneficial at lower temperatures.

Rock salt has endothermic properties which mean it absorbs heat when dissolving, and so for some highway authorities this may have significant implications. More important for most authorities is the fact that salt only begins to depress the freezing point once it is in solution, and hence the objective is to get it in that state as quickly as possible.

As temperatures fall, the amount of de-icing chemical needed to melt a given quantity of ice increases significantly. The effectiveness of de-icing is sensitive to small differences in road temperature. The longer a de-icing chemical has to react, the greater the amount of melting. At temperatures above -6°C both salt and calcium chloride can melt ice in a reasonable time. At lower temperatures salt takes much longer. As the temperature drops, the effectiveness of rock salt decreases until it becomes completely ineffective. Many highway authorities identify a minimum threshold temperature below which salt should not be applied, but as with much of the winter maintenance task, these are not absolute and depend greatly on local climate, geography and road usage, and the resulting road surface temperature.

Moisture

Before a dry de-icing chemical can act it must dissolve into solution. The necessary moisture can come from the ice or snow on the road, from water vapour in the air (humidity) or from liquid added at the point of application. De-icing chemicals are either spread as a solid or, increasingly, as a solution. Changing ice or snow into water requires heat from the air, sun, pavement or traffic friction. Even when the pavement is below freezing, it holds some heat and can help melt snow and ice.

A solid salt particle will dissolve in the first moisture it encounters, provided the temperature is adequate to provide the necessary heat. Dry salt will remain dry unless moisture is introduced from precipitation, humidity, or directly by means of pre-wetting. Once salt starts to go into brine solution, it will continue to melt ice and snow, producing more moisture, which in turn dissolves more of the salt particles. The brine solution will become saturated when all the salt particles have dissolved into the brine. Any moisture added beyond that point would dilute the brine, reducing its effectiveness. Sodium chloride is saturated at about a 26% concentration and is considered most effective at 23.3% (Salt SMART). Other chemicals have different, higher concentrations at which they work most efficiently.
In the event of hoarfrost, black ice, or a forecast of freezing fog precautionary salting may be carried out even if the roads are dry. In the event of a forecast of rain followed by a frost the precautionary salting is usually delayed until it has stopped raining or for as long as necessary to prevent runoff.

**Timing**

Timing is the most important factor in successfully treating ice or clearing snow by chemical treatment. Ironically, the very phenomenon of icing could be caused if salt is applied to the road in the wrong quantity and at the wrong time. When salt is applied early the first precipitation provides the moisture required to break the electrolytic salt bonds and create the brine, hence reducing the possibility of ice or snow sticking to the road surface. It also helps prevent a later build-up and allows any ploughing undertaken to remove snow and ice easier and earlier. Spreading a small amount of de-icing chemical when snow is loose and unpacked melts a little snow and turns the rest to slush. Traffic cannot pack down this slushy snow which is 15% to 30% water, thus allowing snow ploughs to easily remove it. It is better that authorities reapply chemicals as needed rather than initially over-treat a section of road.

Solar radiation warms the road, speeding up melting. Radiant heat may cause the road temperature to rise 12°C or more above the air temperature. On clear nights, road temperatures will be lower than air temperatures. Applying chemicals during blowing snow and cold temperatures will cause drifting snow to stick to the pavement. If chemicals are not used, the dry snow is likely to blow off the cold road surface.

**Chemicals**

The timing, quantity and type of anti- and de-icing chemical applied need to be considered. Dry anti-icing chemicals should not be applied too early in advance of oncoming precipitation, because traffic will blow it off the road. It is also considered unnecessary to spread salt during a snow storm if the surface is dry and the snow is simply blowing across but not packing to the road surface. When solid rock salt is added to dry road it will draw heat from the surface by means of an endothermic reaction, which could in turn lower the temperature of the pavement. This could lead to moisture freezing on contact with the road, and hence those responsible for seeking to keep the road free from ice actually aiding ice formation!

If too much chemical is used, not all of it will dissolve into solution and some will be wasted. Too little chemical may not sufficiently lower the solution’s freezing point. The ice will not melt or melted snow may refreeze and waste the chemical. Those highway authorities that have to undertake regular ploughing operations will set a minimum period of time between application of salt and commencement of ploughing operations to give the salt particles time to dissolves into solution and begin to break the road-ice bond.
Phase Changes

The phase changes involved with water and ice and the effect of chemical are important. The freezing point of water is not static at 0°C, as might be imagined. Instead, it changes in relation to the concentration of freeze point depressant (anti- or de-icing chemical) in the brine solution. The sodium chloride / water phase diagram plots the freezing point of a solution of salt in water. (The line represents the different concentrations that will provide a minimum melt point temperature and below which ice crystals form).

- All points below the curve represent ice crystals along with the solution of sodium chloride and water.
- All points above the curve and in the middle represent sodium chloride crystals along with the solution of sodium chloride and water.
- In the area to the right of the eutectic point there is too much salt, so refreezing occurs.

When salt particles are completely dissolved, further melting of snow or ice dilutes the solution, causing the temperature at which further melting will occur – and at which salt crystals form – to increase toward 0°C. As the brine solution further dilutes, ice crystals form. This causes water to come out of the solution, thereby increasing the concentration of the remaining brine and increasing the amount of time that the salt brine is effective in preventing complete freezing. As the salt concentration in the brine increases, its freezing point drops, e.g. a 10% brine concentration will not freeze until the temperature drops to around -6°C as compared to 0°C for pure water.

The temperature at which the brine will freeze continues to increase as more salt is added and the concentration is raised. The lowest freezing point that can be achieved with sodium chloride is -21°C with a brine concentration of 23.3% by weight. This optimum concentration, which provides the lowest possible freezing point, is called the eutectic point. It is not recommended that rock salt is used much below -10°C.
At different temperatures the same amount of rock salt will melt varying quantities of ice. The table below shows that at -1°C, one kilogram of salt will melt about 45 kilograms of ice. However, as the temperature drop, the same kilogram of salt will melt less ice.

<table>
<thead>
<tr>
<th>Temperature in °C</th>
<th>1 Kg of NaCl will melt</th>
</tr>
</thead>
<tbody>
<tr>
<td>-1</td>
<td>46.3 kg of ice</td>
</tr>
<tr>
<td>-4</td>
<td>14.4 kg of ice</td>
</tr>
<tr>
<td>-6.7</td>
<td>8.6 kg of ice</td>
</tr>
<tr>
<td>-9.4</td>
<td>6.3 kg of ice</td>
</tr>
<tr>
<td>-12</td>
<td>4.9 kg of ice</td>
</tr>
<tr>
<td>-15</td>
<td>4.1 kg of ice</td>
</tr>
<tr>
<td>-18</td>
<td>3.7 kg of ice</td>
</tr>
<tr>
<td>-21</td>
<td>3.2 kg of ice</td>
</tr>
</tbody>
</table>

The objective for the highway engineer is not to melt all the ice, but enough that the bond at the road surface is broken.

**Additives**

In the last ten years the role of additives to reduce chemicals' corrosive properties are coming to the fore, with the introduction of a number of new products. Some of these are agricultural by-products, e.g. derivatives of the sugar production process, and there may also be benefits in making the spreading from the vehicles more efficient. Currently these alternative materials are more expensive, but can be useful in special situations.

The use of salt alone to treat hard packed snow and ice must be done with caution, as in low temperatures an uneven and slippery surface can occur. In exceptional circumstances authorities may apply single size abrasive aggregate, either separately or mixed with salt. This is to assist with traction and does nothing to clear snow or ice. It has attendant problems of causing blockage to drain networks, so authorities are hesitant to use this method.

**Topographic Conditions**

Ice tends to form where topographic conditions, like high banks or vegetation, screen the road surface from the sun. The longer the area is shaded, the more likely that ice will form. Since pavement temperatures are lower in shaded areas, you may need more chemicals there. Studies show that snow melts faster when salt is applied in narrow strips. The amount of snow melted over a long period of time is the same, however, regardless of application width.
Chemicals Used

The most commonly used de-icing chemical is salt (sodium chloride, NaCl), which usually comes from mined rock salt that has been crushed, screened and treated with an anti-caking agent (to maintain spreading properties after a prolonged period of storage). It is one of the most cost-effective, readily available and efficient chemicals for the prevention and removal of ice and snow and is supplied in a variety of granule size and is sometimes applied in solution. Traditionally this has been spread in dry form; known as dry salt. Another two variants are used; with the addition of some moisture either at manufacture at point of spread resulting in the pre-wetting technique (discussed later), and the preparation of a brine (salt solution) that is spread as a liquid.

The growing awareness of the environmental impacts of salt has led efforts to find ways to reduce the amounts entering the environment. There are really only two ways to achieve this:

1. Using something other than salt
2. Optimising salt usage by applying it strategically

A considerable amount of research has been conducted on alternative anti- and de-icing chemicals, although no one chemical has yet been found that can fully replace NaCl, they are used either as substitutes or as supplements around the world.

Including standard rock salt (NaCl) there are four main chloride `road salts'; calcium chloride (CaCl₂), magnesium chloride (MgCl₂), calcium magnesium acetate (CMA). Other chemicals used include potassium acetate (KA), urea and ethylene glycol. The different chemicals obviously have different properties; some work at lower temperatures than NaCl; many have reduced environmental impacts; some can damage road surfaces; and some are volatile and toxic, making them difficult to handle.

<table>
<thead>
<tr>
<th>Chemical</th>
<th>Practical working temperature (°C)</th>
<th>Eutectic temperature (°C)</th>
<th>Eutectic concentration (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calcium chloride (CaCl₂)</td>
<td>-31.6</td>
<td>-51</td>
<td>29.9</td>
</tr>
<tr>
<td>Sodium chloride (NaCl)</td>
<td>-9.4</td>
<td>-21</td>
<td>23.3</td>
</tr>
<tr>
<td>Magnesium chloride (MgCl₂)</td>
<td>-15</td>
<td>-33</td>
<td>21.6</td>
</tr>
<tr>
<td>Calcium magnesium acetate</td>
<td>-6</td>
<td>-27.5</td>
<td>32.5</td>
</tr>
<tr>
<td>(CMA)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Potassium acetate (KA)</td>
<td>-26</td>
<td>-60</td>
<td>49</td>
</tr>
</tbody>
</table>

Properties of anti- and de-icing chemicals (Salt SMART)

The solubility of all chemicals varies with temperature; the lower the temperature, the less the solubility. But the decrease in solubility has a limit, a point where no more of the chemical can dissolve and depress the freezing point; known as the eutectic point.

Each freezing point depressant has its own eutectic point e.g. calcium chloride has a eutectic point of -51°C at approximately 30% concentration. Once the concentration goes beyond the eutectic point the freezing temperature rises rapidly, with 30% salt brine freezing at temperatures near zero. As the amount of solution is reduced and the dilution is nearly complete (approaching water), a slush will form which can be ploughed from the surface before a subsequent application of salt.
Solid calcium chloride (CaCl₂) is both hygroscopic and deliquescent, and hence goes into solution much more quickly than NaCl. It begins absorbing moisture from the air at a relative humidity of 43% and higher, and continues to do so until it dissolves. NaCl, on the other hand, will not begin to absorb moisture until the relative humidity reaches 76%. The hygroscopic and deliquescent properties of calcium chloride are not always an advantage. Additional and costly measures need to be taken to ensure that the relative humidity remains below 42% during storage and handling. Despite having very different chemical properties, a combination of NaCl and CaCl₂ creates a highly effective ice and snow control solution. The CaCl₂ absorbs moisture and releases heat, reducing the amount of time required for the NaCl to go into solution. This quickly produces brine, which sustains the continued brine generation of the two chemicals.

The chloride based chemicals are known to cause significant corrosion of metals, leading to long-term infrastructure and vehicle damage. Urea is considered to have high negative environmental impacts, glycols are toxic to humans and wildlife if ingested, and methanol is volatile, flammable and toxic.

As the research continues in the hope of finding cost-effective alternatives to NaCl, the best way to reduce the amount that is spread on the roads is by doing this more effectively. This can be aided through better forecasting about when salt is needed, and hence the role of RWIS, improved handling practices and improved technology for spreading the salt. The choice as to which anti and de-icing chemicals to use depends on a variety of factors including desired performance influenced by local geography, the need to have a chemical that has minimal negative environmental impact, the effectiveness in anticipated conditions and the cost.

There are standard specifications that refer to the chemical composition and physical gradation requirements for de-icing chemicals, often stipulated on a national basis. The size of the salt granules and the moisture content of the salt are the two main variables. Gradation refers to the particle size distribution is usually classified as either coarse or fine. Larger granule size (e.g. 10mm diameter) used to be particularly popular, and helped ensure that the salt particle was large enough to produce the amount of brine required to generate the melt action that would break the bond of ice and snow from the road surface. These large grades are less prone to be blown from the road by passing traffic, but also had a habit of bouncing off the road during spreading and causing damage to vehicle windscreens. Another disadvantage was that due to the longer time in which the coarse grades would last after spreading, it was more likely that un-
dissolved salt particles would be removed from the road prematurely and hence not be effective in their task. Any ploughing process that moved un-dissolved salt to the side of the road also had the potential to cause adverse environmental effects to vegetation, wildlife and water courses.

There has been a trend to reduce the size of granule used, to the point that 6mm salt is now the favoured option in many countries. The smaller size results in a reduction in windscreen damage, improved spread control away from verges and hence less wastage. On the other hand, finer grades can be prone to caking as well as sticking to the spreader chute. The application of salt is measured in terms of the rate of spread (grams per square metre). The volume of chemical spread varies on the requirements; e.g. prior to ice forming a volume of 10g/m$^2$ can typically be laid in the UK. This figure rises to 40g/m$^2$ if ice has formed and needs to be melted. Similarly, if chemicals are spread prior to snowfall (usually at rates between 5 and 15 g/m$^2$) then small amounts of snow will be melted quickly by the salt, and greater amounts of snow can more easily be removed as the snow will have been prevented from freezing onto the road surface. However, there are no universally accepted salt application rate standards, since they depend significantly on local road conditions, policies, residual salinity, level of service goals, experience and severity of predicted weather conditions.

The moisture content of the salt also has a significant impact on its effectiveness; with larger granules considered to be better for spreading on wider roads and having greater penetration on lying snow. The moisture content also impacts the delivery rate from the vehicles from which it is spread; damp salt has a lower delivery rate than that of drier salt.

In the Alpine countries of Europe the typical salt size is 3.5 mm with a maximum of 5 mm. The maximum moisture content is 1.5% to prevent caking of the salt. Vacuum salt and boiled salt are also used which are more effective at melting snow and ice as there are fewer impurities than in rock salt.
**Surface Type**

Road surfaces generally consist of either concrete or asphalt and there are subtle differences in the way that ice and snow behave on different road surfaces. Concrete surfaces heat up and cool down more slowly than asphalt surfaces, due to their light colour and higher thermal mass.

Asphalt surfaces can heat up to considerably higher temperatures during the day, but once solar radiation stops they tend to cool down more quickly than adjacent concrete surfaces. It has been widely recognised that the rate of spread of salt on porous courses (asphalt) needs to be increased to give the same degree of protection against ice forming, in relation to the rate of spread needed on impervious (concrete) road surfaces due to the higher cooling rate of porous surfaces.

In the UK, the national Highways Agency have issued instructions that the spread rate of salt should be doubled on lengths of Thin Surfacing (porous asphalt) because of its different thermal characteristics when compared to existing surfacing materials.

> **Image courtesy of The De-Icing Business**

It is important to monitor road surface temperatures because they can fluctuate significantly depending on the time of day, extent of cloud cover, sub-surface conditions (e.g. frost penetration, moisture presence and thermal retention properties) and type of road surface.

It is apparent that the selection of which anti- and de-icing chemicals to use is dependant particularly on the geographical location and conditions of operation. There is no one chemical that is suitable for all situations, and hence the highway authority must carefully consider which to use in the light of their unique situation. If the highway authority is operating in a coastal area or marine type environment, where humidity is high and frosting is prevalent, it is likely that a fine gradation of salt will be used. Finer gradations are also used for blending with sand to aid traction (see later).
**Spreading Vehicles**

Salt is applied using various spreading tools and techniques, with the majority being laid from moving vehicles. De-icing chemicals may be applied in either solid or liquid form, however, solid chemicals require moisture to become effective. Many anti-icing strategies are therefore moving towards the use of liquids alone, although with many highway authorities equipped for spreading of solid materials this will continue for some time.

Salt spreading vehicles are available in a variety of capacities; with selection being made dependent on operating environment and route requirements. For example smaller, and more manoeuvrable, vehicles are more suitable for urban areas, whilst urban areas and long sections of route are more suited to larger vehicles. Each highway authority has its own unique requirements, and usually seeks to have a balanced fleet of vehicles based on the likely treatment needs of the roads under their responsibility. Fleets will include vehicles for spreading salt and also ploughing snow, with multi-purpose vehicles also available. With salt spreaders and snow ploughs likely to be travelling on road surfaces that have ice or snow present, the selection of tyres with appropriate tread pattern and material must be considered. Vehicles are likely to require traction control mechanisms and 4-wheel drive to minimise and prevent loss of traction due to spinning wheels.

Hopper style vehicles offer the best control of material application rates and the most dependable service, but they are the least versatile for other operations during the off-season. Some hopper style vehicles are able to have the hopper removed and function as a flat-bed truck at other times so that they can be used all year round by the highway authority.

*A hopper style vehicle spreading salt during de-icing operations*

**Spreading Controls**

Both the moisture content and any additives to the salt affect the delivery rate to the road surface. The delivery rate of damp salt, which is influence by where it has been stored prior to use, is less than that of dry salt and needs to be taken into account. The impact of any additives also need to be understood, since additives can effect the efficiency of the delivery rate, and hence equipment may need to be adjusted accordingly. Within hopper style vehicles a conveyor chain moves material to the discharge location – often the front of the wheels on the driver’s side or along the centreline of the vehicle. Some models have additional distribution points on the passenger side, either in front or behind the wheels to aid coverage of multi-laned highways.

Spreading vehicles are capable of delivering solid and liquid chemicals at a variety of application rates. There are two main methods of spreading de-icing chemical from a vehicle; by a variable speed spinner or via an adjustable chute. The **spinner** method is the most common way of applying de-icing chemicals; in which a spinning circular plate throws the chemical out in a semi-circle. The **chute** distributes the de-icing chemical to a targeted position on the road, and its position does not change as the vehicle traverses the route. The application rate of the material
being spread is controlled by adjusting the speed of the chain used to convey the material to the chute or the spinner. These controls can also record the chronology of actions made by the operator for future analysis and record keeping.

Spreaders are equipped with control mechanisms that regulate application rates to the road surface. Ground-speed spreader controls adjust the application as the vehicle speed fluctuates, such that the intended salt is laid on the surface. Control systems are also able to record the quantity of chemical spread for later analysis and record keeping, and when linked with a GPS system a full history of action taken throughout a road network is provided. The older control systems use a hydraulic circuit to maintain steady application rates, but has the disadvantage that it begins to exceed the desired application rate as soon as the vehicle speed falls below the design speed, resulting in an unnecessary rich chemical mixture being deposited on the road. Newer models use electronic ground-speed controls to provide the consistent application rates. Vehicle speed is monitored from the speedometer and the spreader output is adjusted to maintain a steady output at varying speeds. Some control systems are also able to increase the output rate as additional spinners are actuated to treat steep inclines and turning areas. Hydraulic and electric vibrators and Teflon coatings are used to promote free flow of material. Devices that measure friction can be used to help determine the location and extent to which spreading should occur.

Spread Patterns

Extensive testing has shown that using chemicals strategically allows less to be used. Targeted applications in concentrated locations are more effective than simply spreading the chemical uniformly across the entire width of the road (Salt SMART). A windrow is deemed to be a targeted application of chemical along the centreline of the road. By applying a concentrated mass of material it helps minimise the tendency to bounce or be blown off the road by passing traffic. Application in such a targeted way is achieved using a chute rather than spinner, and can help provide a section of bare surface for two wheels of the passing traffic to have greater friction along. Centreline windrows are not always suitable; they are not appropriate if the road surface is treacherous and immediate de-icing is required. Banked curves are another example where centreline application is less appropriate. Instead, chemical should be placed on the high side of the road.

Chemicals can be usually be spread from a variety of places on a vehicle; from either side at the rear, from either side ahead of the drive wheels and on the centreline of the road at the rear. Discharge along the centreline limits application to only the lane that the vehicle is traversing, whereas use of a spinner or chute towards either side can cover a number of lanes. Application of chemicals ahead of the drive wheels can provide some advantages. By applying sand ahead of the drive wheels the traction of the spreader vehicle can be improved. By applying the chemicals close to the operators car this enables them to monitor the application to ensure material flow is not impeded.

Calibration and Maintenance

Calibration is essential for controlling application rates. Different materials will spread at different rates at the same spreader control setting, so spreaders must be calibrated based on the material being used. Each spreader must be calibrated separately; even individual spreaders of the same model can vary widely in the amount of material they spread at the same control setting. Furthermore, spreaders operate in a very hostile environment - low temperature, lots of moisture, corrosive chemicals - so, they need to be cleaned and checked annually. Fibreglass and stainless or galvanised steel bodies and parts are available but expensive. Fibreglass parts do not corrode, but are damaged more easily during and use and cost more to repair.
Pre-wetting

The pre-wetting of solid salt has become common practice, whereby the salt is moistened prior to being applied to the road in a brine. Pre-wetting allows authorities to retain existing spreading equipment that has been used to spread solid salt whilst increasing the effectiveness of the chemicals spread.

The technique of pre-wetting has a number of advantages over application of dry salt:

- The requisite moisture, which would be provided from ice, snow or precipitation once spread, is instead present at the point of spreading. Hence a solution already exists, and there can be a more immediate effect in breaking the bond between the road and ice or snow. There is also less dust spray from the back of salting vehicles and an ability to better target the chemicals being spread.
- Granules adhere to the road surface much more readily than when dry, therefore less chemical is lost due to initial bounce and scatter, from air disturbance caused by passing traffic or from the wind. Savings in lost or wasted salt of over 20% to 30% are possible (US Roads Management Journal).
- The spreading can be conducted at a speed similar to other traffic since the brine adheres to the road surface better than if in solid form, and hence ant-icing operations can be conducted quickly.
- These in turn leads to a reduction in the volume of chemical required to achieve the same level of service, hence saving money and causing less environmental damage.

Savings from losing less salt to bouncing and traffic action can more than pay for pre-wetting. These benefits accrue from having lower application rates or fewer instances of treatment being necessary. Studies show that the use of liquid based chemicals can yield significant savings for winter maintenance operations, both in terms of operational costs and in reducing the adverse environmental impact due to chemical release (Cypress Bowl Liquid Chemical Case Study, 2001).

A variety of liquids may be used for pre-wetting; with the most common being salt brine (NaCl already in solution), calcium chloride (CaCl\textsubscript{2}) and magnesium chloride (MgCl\textsubscript{2}). Water alone may be used, however, it is uncommon due to the potential for refreezing whilst in the vehicle mounted storage tank, in the supply line to the nozzles, in the nozzles themselves, or on the road.

Pre-wetting may be completed at the material stockpile either prior to or as it is loaded into the vehicles. Spraying stockpiles of salt and vehicle loads has been termed pre-treatment, and this practice is not as effective since the granules are not uniformly coated, the liquid may drain out of the solid material. The most effective method is using on board spray systems mounted to the vehicles which add the pre-wetting liquid to the dry chemical as it is discharged from the chute or at the spinner. This helps eliminate the problem of handling pre-wetted salt that is not immediately used, and is the most common method used. The adjustment of the spray nozzles used in pre-wetting is crucial to reduce wastage. Wetting agents are corrosive materials, so it is important to use stainless steel nozzles and non-contact pumps. Corrosion inhibitors are also added in some cases by the operator and the salt spreaders can be equipped with the ability to re-circulate the chemicals prior to spread to help minimize the stratification process that can occur if left in storage for a period of time.
**Liquid Chemicals**

Some highway authorities are moving to the use of liquid-only applications for some weather conditions. Scandinavian countries have reported substantial salt reductions by using light applications of straight salt brine at the start of storms to prevent roads from becoming slippery (Salt SMART). The benefits of liquid-only applications are the same as those of pre-wetting, except that even less total salt is needed. Liquid anti-icing is particularly suited to road networks and routes with higher levels of service, since the vehicles can undertake operations at higher speed and so cause less hindrance to other road users. Again, ground-speed control systems are utilised to ensure consistent spread rates at varying vehicle speed.

Liquid brine applications are particularly efficient at accurately wetting the road surface to get a head start on maintaining surface friction, although subsequent applications are often required in either solid or liquid form depending on the type, intensity and duration of any precipitation. In order to use liquid-only applications a good understanding of the road surface and sub-surface temperatures is needed, since the concentration of liquid added need to be controlled carefully. Liquid de-icing chemicals will refreeze if they become diluted at low temperatures.

It must be remembered that 80 to 90% of all mileage is done carrying water and therefore this method may be considered less environmentally friendly.

**Zero Velocity Spreading**

With the possibility of dry salt bouncing off the road surface upon application, some highway authorities constrain the speed of their spreaders to limit salt wastage due to the scatter effect at high speeds. Zero velocity spreading occurs when the salt is discharged rearward at the same speed as the spreading vehicle is travelling ahead. The two velocity components negate each other, causing the salt to drop on the road as if the spreading vehicle were stood stationary. Problems such as caking, uneven discharge and mechanical complications have arisen whilst using this process. Another limitation is that although the salt can be spread at relatively high speed, this often ends up as a narrow band near the centreline of the road rather than being broadcast across multiple lanes or even a whole road.
Future Developments

In addition to the factors considered earlier, aspects such as chemical type and handling characteristics also affect the choice made by the highway authority. Research continues on the hopes of finding more cost-effective alternatives to rock salt. However, in the mean time the best way to reduce the amount of salt used is through better forecasting about when it is needed, improved handling practices and improved technology for spreading the chemical. Under dry weather conditions it may not always be necessary to lay salt every time that below zero conditions are forecast. In particular, when there is enough residual salt on the road to deal with the expected conditions. Since it is difficult to measure residual salt along a length of road (though site specific measurements can be made and will be discussed later), highway authorities often take a conservative approach and conduct anti-icing if there is doubt.

There is an increasing need, and legislation appearing (e.g. the Railways and Transport Safety Act 2003 in the UK) to ensure, that pedestrian footways and cycleways are kept clear of snow and ice. Extending the spray of road vehicles can be inaccurate and distribution by hand is labour intensive and time consuming. Hence, new methods of spread have been developed, that enable the delivery of salt or a salt solution to the footways. Some of these systems can be adapted to function in a variety of ways, including as a back pack for authority staff, to attach to a quad bike or to attach to existing road cleaning vehicles that would normally traverse pedestrianised zones. Consideration needs to be given to the type of chemical to be spread, with finer grade dry salt and salt solutions being used since it is more comfortable under foot than salt usually used on roads.
Snow Removal

Ice and snow control do not function independently, and hence although the primary method for ice control is spreading salt and other chemicals, snow control involves both the spreading of salt and ploughing. Salt may be applied to melt through compressed layers of snow, dispersing brine at the interface with the road surface and allowing mechanical removal to be undertaken more easily. If ice, snow and slush can be removed from the road surface by mechanical means, this removes or restricts the need for melting by chemical means. In areas where snow fall occurs, every effort is often made to remove as much snow (and ice) as possible before salt is applied, with developments in equipment enabling this to be conducted effectively.

The objective of mechanical removal is to increase friction, but this can be very difficult, particularly when the snow has become packed. Levels of service requirements are likely to dictate the extent to which snow ploughing will be undertaken. Some highway authorities leave a small amount of snow on the road before salt is applied to help keep the salt from being blown away by the wind or passing traffic. This can in turn increase the amount of salt required to melt ice or snow that becomes packed, and is not considered as efficient in retaining salt on the road as other methods such as slower spreading speeds, pre-wetting or zero-velocity spreading.

During a storm, the snow cover should be removed as completely as possible before the chemical is reapplied, ensuring that the necessary amount of chemical reaches the road surface. Subsequent ploughing operations must also be timed carefully to ensure that the chemical is not removed from the surface prematurely. This impairs its effectiveness and results in high concentrations of chemicals ending up beside the road or in ditches and surrounding waterways. When it comes to ploughing, too early can be as detrimental as being too late.

Snow can either be transferred to the side of a road using ploughing mechanisms or in deep snow conditions can be loaded into lorries for transportation to snow disposal sites. In some locations snow gutters are used to aid removal of snow. These are designed to carry snow away using the force of flowing water, and as such help reduce the amount of snow that has to be transported if snow disposal sites are used. As many urban areas have grown, the traditional snow dumping sites have become less accessible and requiring further for snow removal vehicles to travel before being able to unload. This has led to alternative disposal sites being developed which use snow melting tanks. Snow is dumped into tanks which are heated by a variety of sources including the heat from treated sewage and incineration plants. Such installations can be based in urban areas and thus reduce the distance needing to be travelled by snow removal vehicles before they can commence collecting snow again.

Ongoing operations during the course of a storm may have to be adjusted in response to changing conditions, or the expectation of changing conditions. Hence, it is crucial to have as much real-time information as possible on the state of the road surface, current and forecast weather conditions, and traffic conditions.
3.5.1 Removal Vehicles

Vehicles usually have front and/or side mounted ploughs and are capable of operating at speeds close to that of other traffic in adverse weather conditions, such that high speed ploughing (see below) can be undertaken. For vehicles with ploughs attached to the front, the load capacity of the front axle in particular needs to be considered. Vehicles may have the capability to be configured with a hopper (for dry salt) or tank (for liquid chemical) to enable the spreading of de-icing chemical at the same time as ploughing.

Snow plough with front mounted blade

Grader with side wings

Graders have a high operator position to give excellent vision of the immediate area around the vehicle. This is useful when operating in small areas, particularly urban roads, with cul-de-sacs and varying road widths. They are fitted with a number of ploughs and side wings to remove snow, and thus minimise the amount of snow left that needs to be removed with chemicals.

Loader with large snow bucket attachment
Loaders are a much larger vehicle which usually requires transportation to an area to participate in snow removal. They have a snow bucket attachment to the fore, which is used to remove large quantities of snow. Loaders are likely to be used throughout the year for different purposes by a highway authority, and may also be fitted with ploughs, winds or snow blowing capabilities for the winter months.

Snow blower

Snow blowers are used to open roads in areas with heavy snowfall rates, and often leave some snow on the road that must be treated with abrasive or de-icing chemicals. Some snow blowers have chute attachments that allow for the accurate direction of snow onto trucks. This technique is used in areas with limited space for storage of snow by the side of the road, such that it is transferred to the truck and then transported away.

Images courtesy of Ice and Snow Technologies, LLC

Snow melters were developed before energy costs escalated, and their operation has become prohibitively expensive due to rising fuel costs. They may sometimes be used to provide a solution for unique problem areas.

3.5.2 Plough and Blade Design

Ploughs are fitted with different blades, or cutting edges, for different tasks. The plough type and cutting edge needs to be carefully selected to ensure that is can be mounted on the vehicle properly, operate in the required area and achieve the desired snow clearing performance. Plough blades or cutting edges are available in various designs and configurations for specific operations. Regular blades are made of heat-treated steel or fitted with tungsten carbide inserts to improve durability. Rubber and polymer based blades are also used, and can help to minimise damage to bridge expansion joints, road markings and markers. These types of blades can be used to remove slush from the road surface, but cannot remove heavily compacted snow or ice.

Front mounted ploughs

Front mounted ploughs are one of the most common forms of plough, and are widely used on multi-purpose vehicles that are used throughout the year by highway authorities. Ploughs can either be a one-way design, whereby the snow is moved to one particular side of the vehicle, a reversible design, whereby the snow can be removed to either side of the road, or a ‘V’ shaped design, whereby snow is shifted to both sides of the road.

One-way ploughs are suitable for high-speed ploughing (see below), whilst reversible ploughs are less suitable for large volume removal at speed. Their design means that there may be more snow blown up in front of the plough, thus hindering operator and motorist visibility. Since
reversible ploughs are not used at high-speed, the snow is not thrown as far at the outlet end of the plough and hence there is a greater likelihood of reaming close to the side of the road. ‘V’ shaped ploughs are usually only used in areas with high snowfall rates.

*Front mounted ‘V’ shaped plough*

**Side (wing) mounted ploughs**

Wings are smaller side-mounted ploughs that can be attached at the front or toward the rear of vehicles, on one of both sides. They effectively increase the width of the ploughed path, improving efficiency and proving especially useful in multi-laned clearance. A disadvantage associated with side mounted ploughs is that operator visibility can be impaired, and they may be unsuitable for use in urban areas since they can throw snow beyond the edge of the road and damage roadside features.

**Underbody ploughs**

Under-body ploughs are often used in urban areas where parked cars present a problem for snow removal and in other areas with limited storage space for the snow. They have also been used effectively to clear highly compacted snow and ice, thus minimising or eliminating the need to use high salt application rates. When used in this manner, a hydraulic system may be required to exert sufficient force.

**Plough shoes**

The ploughs used on vehicles in both low and high speed operations are fitted with shoes, or castor wheels, to prevent the blade from dropping into holes or hitting obstructions such as manhole covers or bridge expansion joints. Ploughs are designed to be of sufficient weight to cut through packed snow and ice, in order to minimise the amount of salt required to reach a bare pavement state. This often requires almost all the weight of the plough to be carried on the blade itself, rather than on the shoes or castor wheels. In these cases, the ploughs should be adjusted to minimise the amount of weight carried on the shoes, but the shoes or castors should be close enough to the pavement to absorb the weight of the plough if it strikes an obstacle.
Blade angle

Research has indicated that when the need is to remove large quantities of snow with the least amount of snow being blown up at the front of the vehicle, a $55^\circ$ angle between the blade and the road is the optimum setting. However, if the aim is to cut heavily packed snow and ice, then a $75^\circ$ angle provides more effective results (Salt SMART). Trials with ploughs that combined blades at both angles sounded promising in theory, but encountered problems with slush build up between the blades. It is likely that those highway authorities conducting snow removal on a regular basis will experiment with blade angles based on the available equipment and likely road conditions in their region.

Sliding blades

Sliding blade segments are sometimes used to facilitate thorough clearing of rough or distorted road surfaces. Since less force is required to retract one segment of these blades than on a non-sliding type, these blades are likely to result in less damage to the plough and vehicle from hitting obstacles in the road.
**Ice blades**

Ice blades are used to cut into hard packed snow and ice that cannot be removed with conventional blades. They are often pronged blades, sometimes with replaceable, revolving tungsten carbide inserts, that are mounted on the under-body of vehicles to increase the force capable of being applied to the snow or ice.

### 3.5.3 Visibility Issues

When snow ploughs are used, the visibility afforded to the driver can be severely hampered by the snow cloud created at the front of the blade. Developments are currently continuing with the aim of using aerodynamic airfoils or other means to trap the snow cloud and thus greatly increase visibility both for the driver and other road users. Airfoils are already used by some highway authorities on the rear of their vehicles to help improve visibility for operators and other motorists.

### 3.5.4 High Speed Ploughing

High speed ploughing, whereby the removal of snow is undertaken at a similar speed to other traffic, represents less of a safety hazard on the roads for a number of reasons. By travelling quicker it enables the roads to be cleared sooner, and hence before passing traffic has packed the snow into an increasingly slippery surface. Such ploughing also has the benefit of throwing the snow a sufficient distance back from the edge of the road to minimise snow bank build up, and minimise the need for subsequent ploughing and de-icing operations. However, high speed ploughing is not always possible to achieve, and in some situations ploughing is undertaken at slower speeds. Care is needed in selecting the appropriate routes on which to undertake, since in urban areas throwing snow to the side of the road and beyond may cause damage to roadside features. Ploughs used in high-speed operations are usually fitted with high-strength steel blades with tungsten carbide inserts to increase their durability.

### 3.5.5 Chemical Ploughing

De-icing chemicals may need to be spread at the same time or soon before mechanical ploughing commences, to help melt the bond on the road surface and aid removal. Such a technique of applying chemicals at the same time as ploughing has been termed chemical ploughing. This approach is less efficient and less cost-effective, but may be necessary under certain conditions in the interests of safety and other considerations, e.g. the lack of space on the side of roads for ploughed snow to be deposited.

### 3.5.6 Calibration and Maintenance

As with salt spreading equipment, that used to deal with snow needs to be maintained on a regular basis.

Wear edges are pieces of iron bolted onto the bottom of plough blades which provide protection from the wear and tear on the blade caused by curbs and gutters. They can extend the life of blades significantly and are likely to need replacing on a regular basis to help given equipment a longer useful life.

Application of abrasive material e.g. sand to help increase traction has been shown to cause problems with some snow removal equipment, particularly snow melters.
Friction Enhancement

Sand and other abrasives improve vehicle traction on snow and ice-covered roads. They can be used at all temperatures and are especially valuable when it is too cold for chemical de-icers to work. Sand is the most common abrasive, but slag, cinders, and bottom ash from power plants are also used. Sand is sometimes mixed with salt to help keep it from freezing, with a 10 parts sand to one part salt usually being more than sufficient to prevent freezing in most countries. Mixtures with sufficient salt will melt ice and snow, with the amount of melting dependent upon the volume of sand added.

Abrasives are usually applied only at hazardous locations such as curves, junctions, hills and railway crossings, where motorists must brake, accelerate or maneuver, and on low-speed low volume roads. Some sand and abrasives will be more effective than others. Some studies have indicated that the spreading of crushed aggregate instead of sand, particularly on steep hills and curved sections of road are more suitable for increasing traction. For better traction, material is used with crushed or angular particles. Rounded particles are less effective, and very small particles and dirt are actually harmful to traction.

Since abrasives must stay on the surface to be effective, they should not be used when they will be covered with more snow or when they will be blown off quickly by traffic. Due to some of their limitations, it is accepted that abrasives should only be used when it is likely to take a long time to reach a bare pavement situation.

Heavy traffic reduces the effectiveness of any abrasives, with as few as 8 to 12 vehicles needed to pass to sweep it from snow covered roads, and thus requiring repeated application. The application of abrasives such as sand can also result in large debris deposits on the road, be washed into drainage pipes thus decreasing their capacity or washed into watercourses to become sediment. This may require clean up operations either in the spring after winter road conditions have passed, or at varying times when drainage pipes need to be cleaned. These disadvantages have contributed in part to the drive to find suitable alternative chemicals to be spread, the move towards pre-wetting and have helped focus activity on anti- and de-icing.

Devices which measure available traction on the road surface and are mounted to spreading vehicles are being developed. These systems can help control the application rates of chemicals.

Automated Spreading Methods

Developments are underway with permanently installed, often solar powered, automatic equipment that is able to spray critical locations with a de-icing chemical. The likely place for such installations is bridge decks, which more quickly reach a lower temperature than the surrounding road, and notoriously treacherous sections of road. These can spray the road surface with anti-icing chemicals pumped from storage tanks underneath the bridge. By installing sensors in the road surface a trigger can be set to commence spraying of liquid chemical without the need for a vehicle to visit the area. An example of this is the FAST (Fixed Automated Spray Technology) system in Edmonton, Canada which is beginning to be pre-installed in some bridge construction works. This system continuously monitors conditions, and based on the detection of critical threshold parameters it automatically sprays de-icing chemical just in advance of icing conditions. Developments have also been undertaken to explore the possibility of using abrasive air jets to remove snow and ice from the road surface.
Road Heating

Road heating systems have been in development for some years, with variations undergoing trials and in operational use. Trials in the UK are being undertaken using underground ‘energy reservoirs’ which transfer solar energy collected from the road surface into useable power. Stored heat from the collectors can then be used to heat the road in winter, helping prevent the build-up of ice and snow. Such systems are likely to have all-round benefit, since by absorbing heat from the road surface in summer, the road surface will be helped to stay cool. With the benefits envisaged through less salting being required, maintenance costs of the roads are anticipated to be reduced. The SERSO system in Switzerland uses a range of environmentally friendly heat sources such as geothermal probes, ground water and waste heat from industrial companies.

In Sapporo, Japan, the heating of inclined road surfaces and sharp bends has been tested, with a view to minimising accidents whereby vehicles slide on ice that has deposited on inclined roads. There are limitations to these systems, particularly during heavy snowfall and low temperatures when conditions make it difficult for the heating systems to cope with the demand to melt falling snow. The road surface above any heating elements are susceptible to damage such as cracking and flowing such that it may separate from the underground heating elements. Underground heating systems are also increasingly being installed in pedestrianised areas as these are constructed or renovated, so that the need for de-icing and snow removal in these areas is minimised. Usually a control unit that uses the measurements of weather and road conditions to determine the times to commence, duration and extent of heating to be applied are incorporated into these systems.

There are three main types of road heating systems currently in use:
1. Electrically heated coil systems
2. Gas-fired systems
3. Local energy based systems

**Electrically heated coil systems**

These systems melt snow by supplying low-voltage current to heating coils buried in the road. These can be turned on and off by a controller to accurately achieve and maintain a desired road surface temperature based on weather and road surface conditions. The operating costs of these systems are high.

[Images courtesy of Sapporo City]
**Gas-fired systems**

These systems use gas supplied by a utility provider, and as such are usually a less expensive option. Snow and ice is melted by sending antifreeze that has been warmed by a boiler through special nylon resin piping via circulating pump. In Sapporo, Japan these systems have been installed on sloped roads and sharp curves in areas supplied with gas.

![Image of gas-fired system](Image)

Coiled heating elements being laid before road surface is applied

![Circuit diagram](Image)

Circuit diagram

*Images courtesy of Sapporo City*

**Local energy based systems**

In areas with naturally occurring hot springs, this heat has been used to provide local road heating systems. Hot spring water is drawn from the source using pipes which then transferred along pipes at the side of roads and pavements to melt snow and ice. Whilst these systems cost more to install than the heating-coil and gas-fired systems, their operating costs are lower than the other options.

Bridge based systems are also already in use, which use sections of electrically heated road to melt snow or ice. Point heaters are also used to keep culverts from freezing in remote areas, which would otherwise inhibit ice and snow melt from being removed from the road surface.

**Maintenance Requirements**

The corrosion of equipment is always a concern for highway operators and represents an additional cost over and above the normal material, labour and equipment, but is more difficult to ascertain. Most operators conduct annual maintenance programs for their winter maintenance fleet, with special action being taken to minimize corrosion and maximize lifetime use of vehicles. The vehicles face a demanding environment and in particular the parts in close proximity to the road surface, where they will be in contact with salt and water. These parts are often sand blasted and painted on a regular basis to help maintain in a good state of repair. Changes in the treatment types applied to the road surface are being seen to result in changes in the wear and
corrosion damage to operating authority vehicles (Cypress Bowl Liquid Chemical Case Study, 2001) resulting in fewer parts needing to be replaced on an annual basis.
4 The Weather

Climatology, Weather Conditions & Weather Changes

As well as having the necessary equipment to deal with winter conditions and the knowledge that comes from experience, highway engineers need to have information regarding the likely weather conditions so that they can take appropriate action. Information is highly valuable to the highway engineer and authority, and is the prerequisite to any action that is taken. Every action that is taken is based on forecast and actual weather and road surface conditions. Nowadays a significant amount of the information that is needed to make road maintenance decisions comes from the continuous flow of data afforded by Road Weather Information Systems (RWIS), which are discussed in more detail later.

The critical information needed to support decisions can be divided into three categories:

- **Forecast information**: what will happen – anticipated weather and the likely formation of ice and occurrence of snow.
- **Current information**: what is happening – the current weather and road surface conditions.
- **Outcome information**: what did happen – a record of what actions were taken and the level of service achieved.

National meteorological organisations and private companies provide weather forecast information in a variety of forms and over a variety of time periods. Usually a mixture of short (the next 24 hours) and medium term (the next 2-5 days) forecasts are supplied to highway authorities. Based on these the highway engineers can make provision for the expected eventualities; be that putting more staff on stand-by to be called out, ensuring vehicles are based in the most appropriate location and having them equipped to deal with the likely conditions.

As well as local weather forecasts, highway authorities are likely to make use of models that forecast the road surface temperature and condition. These seek to take into account the changes in microclimate along a section of road and combine this with the weather forecast data to predict how the anticipated conditions will affect the road surface in particular. This is the subject of the next section.

Current information can be found from looking out of the window! However, that will not indicate what the weather conditions are like around a large road network or area of responsibility, and nor will they provide any quantitative assessment of the current conditions. This task is undertaken using meteorological sensors that are usually attached to outstations. The measurements are recorded and then relayed back to the highway authority staff using computer and modem technology. Some forecast providers and most highway authorities use software to compare current data against the forecast weather conditions to indicate how accurate the forecast has been, whether weather conditions are changing and help identify where action that may not have been anticipated purely from the forecast is needing to occur. In marginal climates, the feedback of road surface and site specific weather data to the forecast provider is used to help refine the forecast over the hours preceding anticipated icy conditions.

A variety of outcome information can be recorded; and the extent of this is largely dependent on the technology used by a highway authority. By recording what decisions were made and actions taken, a history specific to a given locality can be built up and referenced in future events. It also provides a recorded history of information and activity in the event that the liability of the highway authority is challenged. There continues to be cases each year in which highway authority decisions are challenged in the courts, often when an accident has occurred, and so it is imperative that the authorities keep as detailed a record as possible. With the introduction of GPS
technologies into the winter maintenance industry, along with more advanced chemical spreader controls, the actions taken by vehicles can be accurately logged and geographically located. Such recording can also help highway authorities plan resource provision and ensure that sufficient chemical stocks are ready for the onset of the winter period.

In marginal climates there are often discernable stages in the progression of the risk involved during a winter period. For example in the UK a distinction is often made between low and high risk periods; and sometimes a third medium risk period is included. Low risk periods are commonly held to be between September and October, and after the peak winter period in April. Medium risk; when severe conditions can arise is traditionally held to be November and March. High risk conditions, when it is anticipated most work will need to be done in salting and ploughing are generally held to be between December and February. Obviously local variations will have an effect on the anticipated boundaries of these periods, and there will exhibit some year to year variation. However, on the whole authorities try to manage their operations as best they can through standardising where possible and having contingency plans in place should the need arise to take action unexpectedly. Such an approach seeks to achieve a balance between economy and the optimum capability to react to severe conditions.

**Road Weather Forecasting**

**Road Weather Models**

There are two approaches to mathematical modelling; empirical and physically based. It is possible to conceive of a continuum from models that are largely built around a set of observations (empirical models) to models that are built around a set of laws (physically based models). Physically based numerical models have been used within RWIS to account for the influence of site-specific geographical parameters on the microclimate of the road.

Numerical road weather prediction models were first developed during the late 1970s and use either a zero-dimensional energy balance, a one-dimensional heat conduction model or a neural network approach. Zero-dimensional energy balance models simulate the energy transfer regime at a location by calculating the unique equilibrium temperature which balances energy flow across the surface, and uses an iterative process. The calculations account for such aspects as direct beam and diffuse radiation, the surface temperature and albedo and latent and sensible heat fluxes. Inputs to the model are likely to include air temperature, dew point, wind speed, cloud amount and type and precipitation. One-dimension heat conduction models function by solving a basic equation using a fully implicit method and are likely to include the same inputs.

To date, many numerical road weather models have been developed around the world. All have the same aim of predicting RST and road condition from a basic forecast of meteorological parameters. Meteorological data is combined with site specific data in a forecast model to predict the road surface temperature over a given time period. In the UK, this meteorological data is issued at midday in the form of a RST forecast curve from which an early decision can be made by the engineers regarding the treating of the roads. Forecast curves (see below) are constantly updated throughout the day, often by nowcasting techniques where the forecast is forced by current meteorological data collected at outstations.
The model can be run twice to produce two forecasts reflecting pessimistic and realistic scenarios, thus enabling the engineer to have a degree of confidence in the forecast. This is important during changeable weather conditions when pessimistic and realistic forecasts can be quite different. Should the pessimistic forecast predict RST below zero, but the realistic predicts RST above freezing, then a stand-by situation is reached and engineers would then wait for further updates. Errors arising from RST forecasts generally fall into two groups and are summarised below.

<table>
<thead>
<tr>
<th>Error</th>
<th>Situation</th>
<th>Potential problems</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type1</td>
<td>No ice forecast but ice occurs</td>
<td>Road accidents</td>
</tr>
<tr>
<td>Type2</td>
<td>Ice is forecast but does not occur</td>
<td>Wasted salt</td>
</tr>
</tbody>
</table>

Errors of RST prediction models

Forecast accuracy has recently been improved by the incorporation of mesoscale numerical models. Mesoscale models currently have a grid length of around 10 to 12km but this scale can still be too coarse so that smaller topographical variables may be disregarded. Also problems can be encountered when the grid-points of forecast models do not coincide with the sensor sites used by the original model. More recently, a site specific forecast model has been developed which uses landuse data to estimate localised surface fluxes, the incorporation of which has improved road weather forecasts internationally.

Climate data is typically point source in nature, and as such presents a significant challenge to meteorologists in the extrapolation of point climate data across a wide spatial domain. The single site approach, mentioned above, has been developed in the UK to the extent that rather than single site predictions using the numerical model, the model is run for thousands of sites (eg for every 50m) around a road network (at varying spatial and temporal resolutions). This development enables the RST to be displayed for any site along the road network at any particular time, rather than simply providing a forecast against which the actual temperature can be monitored for a single site.

Numerical modelling of geographical parameters has the potential to revolutionise road ice prediction systems in their current guise, as RST can now be successfully modelled for any time of the night and at any level of atmospheric stability.
**Road Temperature Forecast Curves**

Chemical and mechanical means are used to prevent ice and snow formation on the roads or help in their removal. The temperature trend of the road surface, rather than that of the surrounding atmosphere, governs the behaviour of any chemical that is spread.

Forecast graphs, typically from noon to noon the next day, provide an estimate of how the road surface temperature will vary, and at what time it is predicted to go below zero.

In the UK, this is issued at midday in the form of a RST forecast curve from which an early decision can be made by the engineers regarding the treating of the roads. Forecast curves are constantly updated throughout the 24 hour period, often by nowcasting techniques where the forecast is forced by current meteorological data collected at outstations.

![Road Temperature Forecast Curve](image)

*Example RST forecast curve on a marginal night.*

**The Decision Making Process**

Operational starting times are intended to be arranged such that sufficient time is available for the salting operation to be completed just in advance (typically 2 hours) of freezing conditions.

There are occasions due to uncertain weather conditions when the decision on the appropriate course of action is best left until the evening or early morning. Manual inspections may be used in the evening or early morning in marginal conditions. Each Highway Authority will follow a Code of Practice specified in advance before the winter season.
5 Road Weather Information Systems (RWIS)

Historical Developments

Road weather information has always been a critical component of winter maintenance decision-making. Traditionally, information has come from a limited number of sources; highway authority staff charged with observing conditions and general weather reports and forecasts. This information may have been relayed between adjacent authorities, and in the early 1980s weather forecast organisations began to issue condition warnings, e.g. road danger warnings, to the authorities responsible for the operation of the highways. These would typically be simple statements such as 'Road surface temperatures are expected to fall below zero at 2am and ice is expected to form on most of the roads in the region.'

Many of the initial advances in RWIS occurred in Finland, Sweden and the UK and have since found application, either directly or in a slightly refined manner, throughout the world. In the early 1980s what were called 'Ice Detection Systems' were introduced. These comprised a number of road weather 'outstations' which collected metrological data from a number of sensors (see below for further details). These 'outstations' could be interrogated by what was called an 'instation' computer as a road authority's central offices or depot. Computer links were used to distribute real-time condition information to a variety of locations, and enabled a closer monitoring of the progress of weather patterns. However, the sensors used on the outstation meant that it was only possible to detect when ice had formed on the road, by which time it was too late to undertake any proactive pre-salting operations.

There were technical limitations to the sensors used that meant erroneous readings could be observed; particularly due to the fact that one of the main chemicals used to treat the road, salt, is hygroscopic. In addition, the sensor used in the road was only present at one location, and hence only able to provide measurements at this one location. It was impossible to know the extent to which the readings being received were representative of the rest of the road network.

The concept of thermal mapping (see below for further details) was developed (at the Universities of Birmingham in the UK and Goteborg in Sweden) to provide a spatial estimate of the likely minimum road surface temperature along a given road network. The first commercial thermal map in the UK was produced for the A9 Highland Region of Scotland in 1984, and the concept of climatic domains (zones) was developed to identify areas which were understood to exhibit similar climatic characteristics under given weather conditions.

Throughout the remainder of the 1980s a flurry of activity led to the installation of what were called 'Ice Prediction Systems'. This method was an improvement over ice detection, since it enabled energy balance models (see previous section) to provide up to 24 hour prediction of road surface temperature and condition. This solution also offered the possibility to plot actual recorded measurements over the 24 hours against the forecast curves, to provide the engineer with an indication of the accuracy of the initial forecast. Depending on the severity of any difference between forecast and actual measurements, the forecast curve may be updated. The thermal mapping concept was developed to provide maps for a variety of air stability classes (extreme, intermediate and damped) for each climatic domain. The minimum road surface was forecast and maps of the road network were colour coded to show which roads were likely to fall below zero under given air stability and in the different climatic domains.

In the UK these developments led to what became termed the National Ice Prediction Network, and continued to be developed, such that the various manufacturers of weather stations and software and the weather forecast providers could communicate interchangeably. The model developed in the UK was reciprocated around the world, and in particular in countries with similar marginal winter climates. With the use of personal computers in some nodes of the chain, the service provision was limited by processor speed and the inherent limitations of the
communication protocols that had been developed at that time. It would take approximately 30 minutes to run an energy balance model for one location, and the modems used to connect to each outstation and collect the meteorological data were slow and typically unreliable. The fixed climate zones and thermal map types were necessary simplifications to make the system usable in real time. During the 1990s technological developments, and in particular the increase in processing power, has afforded an improved speed of service delivery. However, the same model of RWIS has typically been in place in the UK and throughout the world with little further refinement or revision. From 2000 onwards, significant developments have begun to be made, initially in prototype and these are gradually finding their way into the commercial arena. The details of these developments are covered in more depth in their respective areas of discussion below.

A RWIS is the most effective decision-support tool available for winter road maintenance, which needs to be interpreted by a trained practitioner. Based on the current and forecast road condition information the highway engineer can determine the window of application for anti- and de-icing chemicals to be applied and for snow removal operations to commence. By strategically timing operations the safety of highways can be maintained whilst going some way to optimising the quantity of material applied to the road surface. RWIS are not comprised solely of sensors embedded in the road or mounted on roadside towers. On a broader level, they can include any device that captures and transmits road weather information; such as mobile infrared thermometers which are either handheld or mounted on a vehicle or electronic spreader controls which monitor prescribed chemical application rates and location. Static outstations are not necessarily the best solution for all situations. They are extremely valuable for large road networks, but less useful for monitoring urban road systems. In these environments, local conditions can vary considerably due to the presence of buildings and heavy traffic, and as such vehicle mounted and hand held sensors can be more effective in tracking localised variations in road surface conditions.
Sensors and Equipment

Sensor based road weather information systems (RWIS) have been in use for over 25 years by highway authorities around the world, and are used extensively in Japan, Europe and North America. A variety of sensors and equipment have been developed to both measure and monitor road and weather conditions. Individual sensors are usually attached to a recording device; and usually a number of sensors are mounted to a tower to create an outstation. These suites of monitoring devices play a vital role in the RWIS, and are sometimes in and of themselves referred to as a RWIS.

RWIS networks support winter road operations in a number of significant ways:

1. They improve the accuracy of decision-making by providing an understanding of actual road temperatures, trends and forecast accuracy.
2. They provide a monitor of road temperature, wet/dry status, freeze point of the solution on the road, the presence of chemicals and concentration as well as subsurface temperatures.
3. By installing atmospheric sensors on a tower, they can provide real-time localised information about the atmospheric conditions; such as precipitation, relative humidity, dew point, air temperature and wind speed and direction.
4. Weather forecast providers can use the information to assist in the provision of localised road weather forecasts to help the highway authorities decision making. The data can also be used to verify the quality of the weather forecasts.
5. Ant-icing and de-icing chemical usage can be optimised through more accurate deployment of equipment and application of chemicals.
6. Additional sensors can be added to RWIS to further support the highway authority in maintaining the road network; e.g. devices to measure road friction and snow cover, and automated liquid de-icer application systems.

Often national highway networks e.g motorways will have a separate network of outstations than those operating within local authorities, although there may be some sharing of data, to assist in service provision. Some initiatives e.g. MesoWest in the western US states, seeks to provide a co-operative data exchange network providing access to weather observation data from thousands of sites. However the fact that the outstations have been installed over a period of decades and with a variety of technological advances occurring in this period, this can mean that not all authorities have the necessary hardware and software to access the data. Differences in communications protocols have been implemented by a variety of equipment suppliers, which has led to further problems in ensuring the data can be easily shared. However, moves are underway to implement open communication protocols that will help ensure that these problems do not continue indefinitely and that integrated RWIS are in operation.

Sensor data provides site-specific information that confirms what highway authority staff may already be thinking, and may also contribute new data that enables fresh insights that require a change in strategy. It is the purpose of a RWIS to assimilate the influence of the meteorological and road data to develop a picture of how RST is changing at a given site. The actual data from the local climate and road can be incorporated into road weather models (see previous section) to forecast road conditions. This forecast is then thermally projected around the road network by means of thermal maps. As such, not only is an understanding of current conditions provided, but also a forecast of anticipated conditions around a road network; and thus when and where freezing or snowy conditions will occur.

Many commercial RWIS have been developed around the world and the SIRWEC web site gives the internet sites for a range of companies. The following descriptions are not meant to endorse any particular RWIS – but are illustrative of what is available. The European standard (CEN7TC 337 WI 00337006) is currently under review and it is hoped that RWIS systems will comply.
Outstation Structure

Outstations are likely to include some or all of the following:

- Road sensors in travel lanes to measure; surface temperature, sub-surface temperature, surface condition (dry, wet, frozen), amount of deicing chemical on the road, freezing point of the road surface.
- Atmospheric sensors adjacent to the road to measure; air temperature, relative humidity, wind speed and direction, precipitation.
- A power source; usually a battery which is supplemented by either a mains electricity connection or solar panels for recharging purposes.
- A datalogger; to which all the sensors are connected and which translates and records the signals received from the sensors into a format that can be communicated to another computer.
- A communication device, such as a modem, to allow remote collection of data and transfer of new datalogger programs and other software updates without visiting the site.

Most of the sensors on an outstation reside non-obtrusively above the road, affixed to a tower. The array of sensors that are typically part of an outstation are used to measure wind speed, wind direction, air temperature, humidity and precipitation. However, some sensors – and in particular those measuring and monitoring road conditions – either at the surface or sub-surface – reside in the road. More sophisticated outstation arrangements may include sensors which measure the following; road condition, present weather and visibility.

Wind speed and direction

Wind speed and direction measurements will be made either by a combination sensor or by individual sensors. A common type of wind speed sensor is the three-cup anemometer, which uses an arrangement of horizontally mounted cups to sense wind speeds. As the wind turns the cups, this movement is converted into an electrical signal that is converted into a wind speed by the data logger or software. There are a variety of types of anemometers, which vary in appearance, but have the same basic principles of operation and reporting. The threshold and resolution capabilities are key specifications for anemometers. Threshold refers to the wind speed required before a sensor can take and report a reading. With three-cup anemometers this is the
amount of wind required to begin turning the cups. Resolution refers to the minimum unit value that can be reported. More recently hot wire anemometers, with no moving parts, have become cheap enough to use in RWIS systems.

**Air temperature and humidity**

Air temperature and humidity sensors are crucial for predicting or detecting conditions where frost may appear on road surfaces. Typically a single sensor provides both air temperature and relative humidity measurements. To minimise errors induced by solar heating, the sensor is typically mounted in a solar radiation shield.

**Precipitation**

Volume of precipitation in a given period and hence the rate of falling precipitation can be measured, although some systems just measure the occurrence or not of precipitation. Precipitation type (rain, sleet, snow etc) is difficult to determine using conventional rain gauges and therefore present weather sensor (see below) are used.

**Road condition**

The identification of road temperature and condition is also crucial for the accuracy of a RWIS. These sensors report the road surface as either being wet, dry or frozen, and usually report the road surface temperature as well. Sensors are embedded flush in the road, as well as sub-surface, generate data that can be used to identify trends. Road sensors are usually located just outside the wheel path of vehicles, preferably at a location that is known to freeze early. Some road sensors are required to be placed in the wheel track to effectively clean the sensor heads. Some of the methods and approaches used to determine road condition are discussed below.

**Visibility**

Visibility sensors measure meteorological optical range, and can be extremely useful in low-visibility, fog-prone areas. These sensors typically use infra-red forward scatter technology, with a limitation being that anything in the optical path that attenuates or scatters the infra-red beam, such as dirt, or even spiders webs, may cause erroneous readings. To avoid this problem multiple sensors can be used to check and adjust for any contamination errors.

**Present weather**

Present weather sensors are able to detect indicate the cause of reduced visibility, identify precipitation type, measure the intensity and accumulation of precipitation and estimate snow accumulation. These function by estimating the water content of precipitation with a capacitive device and combining this information with optical forward scatter and temperature measurements and processing these through algorithms to identify the weather type.

Some sites are also equipped with video cameras so that photos of the roadway can be taken and viewed remotely.
Passive, Active & Remote Sensors

A common approach used in road surface sensors is monitoring of road surface conductivity, which changes as road surface conditions change. Where anti- or de-icing chemicals are in used, surface conductivity is also an indication of the concentration of chemical on the road. This is vital information, since the presence and concentration (known as residual salinity) will affect the actual freezing temperature of the road surface.

Passive road sensors sit in the road without any heat energy being transferred to or from the sensor. They attempt to measure road surface condition and residual salt using conductivity or capacitance or vibration or radar or other methods.

Active sensors artificially cool and reheat a section of the sensor by up to 2 degC to help provide an advanced ice/frost warning using Peltier and other methods. If the sensor is cooled by 2 degC and ice is detected on the sensor then a warning is issued.

Remote sensors use infra-red, microwave radar or laser techniques by either mounting the sensor above the road or by bouncing a signal across a road from a transmitter to a receiver.

After snow and ice have been melted and ploughed and the road surface has returned to a bare and dry condition, the legacy of operations remains in the form of a chemical residue on the road surface. This chemical will be activated with the next precipitation event, so the highway engineer needs to know about it and take this into consideration when deciding on the next action to take. A road surface condition sensor can provide this kind of information.

Two examples of Passive Road Sensors.

Mobile Sensors

Infra-red road temperature sensors can be mounted on a salting vehicle and the amount of salt placed on the road can be varied accordingly. Also experiments have been carried in some countries to mount an infra-red temperature sensor on buses and taxis which report the road temperature back to a central control room via Mobile phone and GPS.
Other Measurement Methods

New road sensors are being tested continually to give the road engineer more information. The measurement of present weather and visibility is often carried out in fog prone areas.

Many road engineers now use infra-red/visible video cameras to monitor road conditions. The cost of such cameras has dropped considerably recently and communication costs have also fallen.

Ice cameras are now available that for a given field of view the camera provides a detailed digital image of the road that is colour coded based on interpreted road condition (ice, snow, wet, dry etc).

Images are usually polled at a low frequency; perhaps every 15 or 30 minutes, although the cameras obviously have the facility to update the image at much higher frequencies. Images are archived for a period of time, and whilst these images have not been used in traffic enforcement applications yet, it is possible that a high frequency of image capture and greater emphasis on image retention may result in the cameras installed on outstations being used for applications far beyond those purposes originally imagined including number plate recognition, road charges etc.
The Role of Road Weather Outstations

The accuracy of road weather forecasts obtained from forecast providers is monitored by automatic weather stations strategically placed on the highway network to collect localised ‘point source’ information.

Traditionally the decision whether or not to treat the road network is achieved using a network or road surface temperature sensors (attached to a weather station, sometimes called an outstation). These are used to assist in the forecasting, modelling and monitoring of changes in road conditions.

Data transfer then takes place from sensors to a master station computer where the data is combined with regional weather information in a road weather prediction model. The end product is a simple forecast of road conditions which is distributed to the highway engineer.

While the system is used primarily for management and decision making during the winter months, it is also used effectively during the summer and spring to plan projects such as asphalt overlay.

Outstations usually incorporate both atmospheric and pavement sensors that provide real time data. The atmospheric sensors are usually attached directly to a tower or arms that hang from the tower. Pavement sensors on the other hand are buried in the road and provide condition information as to whether the pavement is near freezing or if there is already ice accumulation.

‘Outstations’ usually have the ability to store data locally and transfer data to an ‘instation’ using a common protocol. Data may be stored in a ‘bureau’ acting for several highway authorities. Highway authority staff access the real-time pavement and atmospheric data via computer workstations at their maintenance office.

*Image courtesy of Alaska’s Road Weather Information System*
Real time information enhances an operating authorities ability to conduct road maintenance operations in a timely manner. Actual weather and road conditions can be monitored against forecast conditions, and the information can be used all year round to help assess...

Several pavement sensors can be connected to a single outstation.

Outstation’s have limited local intelligence for processing data, so the data is transmitted to a central server, which is typically located in the highway maintenance facility offices. This provides communication, collection, archiving, and distribution of data. The raw data is used directly, or in conjunction with data from a weather forecast provider to prepare forecasts. Forecasts can be used to predict site-specific weather and road conditions.

Role of internet, intranet, satellite and dial-up lines

- Sensor data collected and stored locally in datalogger at outstation
- Central server contacts the outstation at fixed intervals and collects the outstation data
- Data is processed and stored by the central server
- Information made available to end users; often through internet based applications
- Information can be sent to other organisations
- Integration of other information e.g. satellite images
- Mobile solutions e.g. using GPS can be integrated into the system

Software is used to present a comprehensive and continuous flow of data about a section of road.

The term nowcasting has become familiar to describe the use of real time data for short term forecasting purposes. Nowcasting relies on the data from outstations combined with weather radar and satellite information.
5.3.1 Maintenance Requirements

Sensors installed in outstations frequently have an in-built test function to alert the user that a problem has arisen. Tests can be done by comparing readings from the different sensors with those taken from an additional measuring device taken into the field. It is usual for annual maintenance contracts to exit, such that prior to the winter period commencing all outstations are visited and checked to be in worthy operating condition. Typically there are three types of maintenance plan for outstations:

- **User maintained**: the outstation supplier trains the user to maintain and repair the equipment.
- **Supplier maintained**: the supplier performs all preventative and corrective maintenance. The supplier is likely to have remote diagnostic capabilities, so that a problem can be identified before a member of staff is sent to the site.
- **Third party maintained**: a third party performs maintenance and repair services. The third party is usually approved by the original equipment supplier and is trained in the work necessary and should receive strong support from the supplier and have tools available for diagnosing problems remotely and on site.

5.3.2 Locating Outstations

Highway authorities and transportation departments usually operate a network of meteorological stations strategically located along the road network.

The exact positioning of the outstations varies from country to country. In the UK, they are located at sites where they measure typical variations and not locally cool or warm microclimates. However, the opposite is true in other countries as outstations are located at sites which are particularly prone to icy conditions (white spots).

When locating an outstation the need for power and communication supply needs to be taken into consideration. There are moves to make this easier, with the inclusion of solar panels and mobile communication technology enabling sites to not be limited to those capable of receiving fixed power communication supplies.

A poorly chosen site can result in incorrect readings, service difficulties or even damage from passing traffic. The site should not be sheltered in such a way that sensor readings give a false impression of the situation closer to the road. At the same time sensors and the outstation should not be located too close to the road that wind from passing traffic will give inaccurately high readings. The height of sensors above the ground, as well as their orientation, can also affect sensor readings and needs to be taken into account when selecting locations and installing equipment.

**Site surveys**: determine optimum site location for the installation of outstations; consider availability of power and telecommunications and the suitability of sensor locations.

A RWIS network usually comprises a number of individual sites. The information gathered is valid at the site from which it is being obtained, but it can also be interpolated between sites (using thermal mapping techniques). The number and spacing of sites in the network is dependent upon a variety of factors including; topography, soil type, land use, microclimate zones, proximity to utilities, road classification. Generally, the greater the variability in these factors, the more sites will be required in the network.
5.3.3 Deployment Strategies

Outstations are relatively expensive and time consuming to install and therefore the minimum number of outstations for a particular salting route network is required. In the past a ‘rule-of-thumb’ was to install an outstation every 50 to 150 km depending upon the local geography. This is probably equivalent to one outstation for every 2 or 3 salting routes.

5.3.4 Trouble Spots

Some road authorities like to put their outstations in cold or exposed locations where, from experience, they have had trouble in the past. This gives a rather negative view of the temperature of the road network. Other road authorities prefer to place outstations in a cross section of cold locations, average locations and warm locations.

5.3.5 Micro-climate Representation

Thermal Mapping is often used to locate ideal outstation locations.

5.3.6 Virtual Outstations

Virtual outstations can be located on salting routes that have not got a conventional outstation. Predicted forecast graphs of expected road surface temperature can be provided for these virtual sites for operational purposes.

Highway departments usually supplement RWIS data with weather forecast data they purchase from weather forecast providers, and it is becoming more common for bordering states or neighboring municipalities to share RWIS sensor and forecast data.
Thermal Mapping

Road weather models are presently restricted to the production of a single forecast curve for the sensor site from which the meteorological data are acquired. Hence, the RWIS requires a means of projecting this forecast around the road network. Pioneered during the late 1970s, thermal mapping is a process which measures the spatial variations of nocturnal RST along a road network. Thermal mapping surveys are conducted by using a vehicle mounted infra-red thermometer connected to a datalogger. Other links to the datalogger include a manual keypad which allows for driver-intervention, but more importantly is the connection to a distance measuring device which enables the infra-red thermometer to measure the energy flux $E$ from the road at set intervals. This is converted to RST by using the Stefan Boltzmann equation:

$$E = \varepsilon \sigma T_0^4$$

Where $T_0$ is RST, $\sigma$ is the Stefan Boltzmann constant and $\varepsilon$ is emissivity.

On marginal nights, where the road surface temperatures fluctuate around freezing, the presence of a few weather outstations can be of limited benefit to the highway engineer. The data collected is only representative of the site under study, and hence assumptions have to be made for the sections of road in-between sensor sites.

In the 1980s the concept of thermal mapping was developed at the Universities of Birmingham UK, and Goteborg Sweden and enabled interpolations between outstations to be made. A vehicle mounted infra-red thermometer was used to measure the road surface temperature (RST) at set spatial resolutions across a road network. The magnitude of this temperature variation is dependent on the prevailing weather, but the actual pattern of RST variation remains similar on a nightly basis. For example, sections of road under trees and in urban areas are always the warmest sections of the network, regardless of weather conditions (something termed in urban areas as the urban heat island UHI).

The traditional requirement was for surveys to be made under varying weather conditions; five surveys were standard under three pre-defined weather conditions. The three weather conditions selected are damped, intermediate and extreme.

Thermal mapping techniques have remained largely unchanged for the last twenty years, despite the high cost involved in undertaking five (or more) surveys under the three pre-defined weather conditions. The maps themselves are limited as they only provide a static prediction of what the minimum temperature will be across a road network.

Thermal mapping data are initially displayed graphically as a pattern of temperature variations along the survey route on a given night. Such graphs are called thermal fingerprints, where the amplitude of the thermal fingerprint displays the departure of RST from an averaged value against distance for a particular route on a particular night. The amplitude of the thermal fingerprint is dependent upon the weather conditions over the day preceding and during the mapping run. During stable conditions variations in RST become much more apparent.
Thermal Fingerprints showing the impact of stability on residual road surface temperature amplitude

Used to predict icy stretches of road during winter nights, thermal mapping is the measurement and visualisation of road surface temperatures for road ice prediction purposes.

To account for this variation, thermal fingerprints are classified with respect to atmospheric stability. This is achieved by considering average wind-speeds and cloud cover over a 12-hour period preceding the mapping run, which are then used to produce a stability classification for the fingerprints.

<table>
<thead>
<tr>
<th>Surface wind-speed (m/s)</th>
<th>Thinly overcast or ≥ 4/8 octas of low cloud</th>
<th>&lt;4/8 octas cloud</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;2</td>
<td>G extreme</td>
<td>G extreme</td>
</tr>
<tr>
<td>2-3</td>
<td>E intermediate</td>
<td>F intermediate</td>
</tr>
<tr>
<td>3-5</td>
<td>D damped</td>
<td>E intermediate</td>
</tr>
<tr>
<td>5&gt;</td>
<td>D damped</td>
<td>D damped</td>
</tr>
</tbody>
</table>

Classification of fingerprints with respect to Pasquill Gifford stability classes (bold) and Thornes classification (italics)

With the exception of some extreme nights where cold air advection may be evident; the general temperature trend for each route remains the same, with the same sections being relatively colder due to microclimates caused by systematic variation in geographical parameters.
In theory, thermal fingerprints trends surveyed in the same stability classes should be similar. However, combination of random and systematic error can mean that this is rarely the case. For example, Belk (1992) showed that temperature differentials on a route within the Peak District varied by 5ºC over five similarly extreme nights.

**Random Errors**
- Varying road emissivity
- Detector sensitivity
- Atmospheric absorption & attenuation
- Lens waveband too small
- Equipment not warmed up
- Change of lanes due to slow traffic

**Systematic Errors**
- Instrument temperature range exceeded
- Error in milli-volt to RST conversion
- Dirty lens and condensation
- Radiation from vehicle
- Varying tyre pressures

**Random and systematic errors associated with thermal mapping**

Hence, in order to achieve fair coverage, a sample of thermal fingerprints is collected during various weather conditions before thermal maps are drawn up for each individual stability class. Thermal maps are then plotted in a GIS (Geographical Information System), an example of which is shown below. The thermal map of microclimates is then combined with the daily regional forecast curve to complete the prediction component of the ice prediction strategy of many local UK councils.

**Example of thermally mapped data displayed in a GIS**

Empirical methods provide an alternative methodology to thermal mapping for extrapolation. Since the 1970s work has been ongoing to develop empirical local climatological models for
thermal projections between outstations in Sweden. These models are now used commercially and demonstrate that variations in RST can be accurately explained by the influence of several geographical factors and prevailing synoptic conditions. However, in the UK, thermal mapping remains the standard methodology used for interpolation between sites.

Pioneered during the 1970’s, thermal mapping is a technique used to measure the spatial variation of nocturnal road surface temperature (RST) along a road network. Thermal maps have been an integral component of Ice Prediction Systems for the last 20 years providing the means to spatially extrapolate site-specific RST forecasts around a road network. Once the colder sections of the road network are identified, the highway engineer can target specific sections of road with de-icing chemicals to mitigate the hazard of ice formation. Although the thermal mapping approach is fast being superseded by more advanced spatial modelling techniques, there is a need to continuously improve the methodology as it still provides a useful validation tool for model development.

Many of the systematic errors can be avoided with careful preparation of equipment. Furthermore, a huge step forward in recent years has been the proliferation of geomatics technology. Initially, distance measures were taken from the speedometer of the car. This meant that errors could creep in caused by subtle differences in speedometer accuracy, cornering at different angles and variations in tyre pressures. Global Positioning Systems (GPS) have revolutionised this by almost entirely eliminating systematic distance errors and has the added advantage of facilitating the rapid visualisation of RST data in geographical information packages (GIS). However, minor problems do exist even when using GPS as errors can occur where the signal becomes blocked or reflected by buildings and trees. The result is diminished fix accuracy due to a reduced signal and hence, care must be taken when using GPS to plot mapping runs in built up areas, forests or deep valleys.

Random errors in the thermal mapping technique have proven more difficult to address. First and foremost, IR cameras typically have a specification accuracy of ±2°C. Furthermore, the accuracy of the reading is dependent on the correct emissivity being set for the surface under study. Despite 0.95 being a universally accepted value for a road surface, it greatly oversimplifies the situation. Different road surface materials (i.e. asphalt/concrete) will have slightly different emissivities which will further vary depending on the road weather conditions (i.e., wet/dry). The problem of emissivity variation is enhanced due to the fact that calculated temperatures are extremely sensitive to even the smallest change in emissivity. A change in emissivity to 0.85 from 0.95 would produce a temperature difference of 8°C.

Thermal Geomatic Surveying

Advances have been made in addressing some of the limitations of the thermal mapping process, and typically build on the existing methodology and improve the accuracy whilst reducing the associated cost. Thermal Geomatic Surveys allow the necessary data to be collected in a single survey rather than the five associated with thermal mapping. These surveys not only measure the RST using an infra-red thermometer, but also record the sky-view factor (see section) which is a measure of the degree of sky obstruction by buildings and trees, along a road network. By combining this information with other road data, e.g. latitude, longitude, altitude, slope, aspect, road construction, thermal residual temperature, land use, cold air pooling index and traffic volume, a dynamic modelling approach to road weather prediction can be made, rather than relying on paper based maps.

It is also possible to take into account changes in road construction and new building development comparatively easily.
Salting routes colour coded according to suggested action based on forecast road temperature and conditions

Road Surface Temperature – High resolution forecast for the road network available from the ‘drill-down’ function

Road Conditions – High resolution forecast road condition data for the road network available from the ‘drill-down’ function

Forecast Curve - Road Surface Temperature curve for a single site on the road network

The Role of the Sky-View Factor

The sky-view factor (SVF) is a measure of the degree of site sky visibility and is commonly used in energy exchange studies. The SVF is a dimensionless parameter represented as a value between zero and one, and quantifying when the sky is obscured (e.g. 0 = tunnel) or exposed (e.g. 1 = open sky) respectively. The SVF has been demonstrated to have a considerable influence on the heating and cooling of the road surface, and yet it has proven to be challenging to calculate with a number of different methodologies used. Geometric methods to calculate SVF were common in the 1980s where urban canyons were modelled in a simple fashion by considering rations of height to width. However, in more recent years photographic methods have come to the fore, which theoretically offer increased accuracy. The use of a fish-eye lens allows an image to be acquired of a location showing the horizon throughout 360°, which can subsequently be analysed.
to provide a value of the SVF. The SVF controls the amount of incoming solar radiation to a road surface (shadowing) and also limits the amount of outgoing long-wave radiation.

Some user intervention is required to delineate sky pixels from non-sky pixels in the images recovered. Digital imaging and processing techniques have allowed the process of calculating the SVF to be partially automated and occur in real time with the video capture of images rather than collection of still photographs. However, to allow algorithms that are used to automatically delineate between sky and non-sky pixels to function in real time meant that compromises were required. In particular, the size of the captured image is important; with low resolution images being quicker to process but obviously a trade-off arises between processing speed and accuracy.

Data Presentation and Interpretation

The weather and road condition information is now being disseminated to a wide range of transportation users and operators to aid in their decision making. In some countries this includes the travelling public and transit operators.

Highway authorities need to keep track of inventory, operators and fleet at their disposal, weather patterns, road conditions and actions taken in their winter maintenance operations. Any management system that is put in place, whether a sophisticated electronic solution or manual, paper based, is only as reliable and effective as the data that is fed into it. The further back historical records go, the more useful the information can become. If records are kept over a number of years it becomes apparent what resources are needed and weather patterns are likely. By monitoring usage e.g. of de-icing chemicals in a given winter, re-ordering of stocks can be undertaken when levels reach a given point. A five year average is recommended by some authorities to determine a reasonable amount of chemical to order, whilst bearing in mind the possibility of unseasonable or prolonged cold spells and taking in to account experience and knowledge of the local situation. Any new road that has been added to the network since the previous winter also needs to be taken into account.
Tracking and recording usage on a shift-by-shift basis and to the point of how much was spread at any location on the road network not only aids the re-ordering process but ensures a comprehensive log is kept should the authority receive and queries or actions against it claiming inappropriate action was taken. The calibration of both chemical spreader controls and RWIS equipment on a regular basis helps ensure that the best possible data is available to support decision making.

**Winter Maintenance Management Systems**

The goal of winter maintenance strategies is to achieve the desired level of service (see earlier) requirements by using available resources cost-effectively whilst minimising the use of chemicals. In order to achieve this the highway authorities need three types of information:

1. **Forecast information** (what will happen); for predicting upcoming storms and potential icing events.
2. **Current information** (what is happening); providing road surface temperatures and conditions.
3. **Status information** (what did happen); recording what was done and the level of service achieved.

Various international research groups have attempted to derive more sophisticated management strategies such as COST 344 in Europe and MDSS (Winter Maintenance Decision Support System) in North America.

**The Role of Geographical Information Systems (GIS)**

Increasingly Geographical Information Systems are used by road authorities to store all information about the road network including salting routes. GIS can now be used to help predict which salting routes require treating by combining geographical, road construction and meteorological information every 20 m around a road network (see XRWIS).

**The Role of the Internet**

The internet has now replaced dedicated road weather workstations and is much cheaper and faster to update.

**The Role of Global Positioning Systems (GPS)**

GPS was developed in the 1960s by the National Aeronautical and Space Administration (NASA) in the US and the US Military. Its main use was for high precision positioning and navigation by the trilateration of information from the 24 satellites in the system. GPS units gather information regarding the distance of the satellite to the receiver and correction data to account for errors in the timing of the signal as it passes through the atmosphere. The data from each satellite is processed by the GPS receiver, where they are combined to provide positional data to the user. Raw GPS data is communicated by means of a standard protocol, of which the most common is the National Electrical Manufacturers Association (NEMA). The data is coded into a series of ASCII sentences containing information on position and signal quality, and it is this data that has enabled GPS to be used in diverse applications.

The collection and display of spatial data has never been easier. GPS enables road engineers to track the salting trucks and snow plows' locations and can be used to alert drivers of snow-
covered obstructions. Theoretically, a GPS-equipped fleet could save time and fuel by enabling engineers to send the nearest salting truck/plow to areas with deteriorating weather conditions, accidents or emergency medical situations.

**International Standards**

A number of international standards for the design and maintenance of RWIS systems have been proposed. However each country has tended to produce their own requirements and little success has yet been achieved to standardise road weather practice.

A European Standard for RWIS “Winter maintenance equipment – Road weather information systems – Product description and performance” (CEN7TC 337 WI 00337006) has been established and is currently in consultation.

In North America the NTCIP 1204 (National Transportation Communications for ITS Protocol Environmental Sensor Station Interface Standard – Version 02) suggests standards for RWIS sensors that are close to approval.

**International Approaches & Systems**

The RWIS plays a significant role in the operations of highway authorities, and in particular during the winter period as described in this guide. It is common practise for authorities, whether on a national or local level to have in place a winter maintenance plan. This outlines the different aspects involved in providing the service in a given region; from those responsible for decision making, procedures and priorities to those responsible for operational actions. These plans are revised as new developments in the RWIS are implemented and function as reference sources to help ensure that all those involved in the task of ensuring safe passage of transport on the roads are fully briefed and kept up to date of developments.

**Information Provision For End Users**

The highway engineer has to convert the information received from the components of the RWIS at their disposal into a decision as to which of any roads to treat, and when these need to be treated, and how much chemical should be used. This is a difficult decision, with many variables influencing the final decision made, and a short time period in which the decision must be made and resources mobilised. Any developments to significantly aid this process are on the whole warmly welcomed by the practitioners, but also need to be tested thoroughly to help instil credibility and confidence in the tools by the highway engineer.

**Networking and Data Sharing**

Common language Incompatibility of RWIS hardware and software from different manufacturers has made for a modern day Tower of Babel, but work is under way to eliminate that problem. The Joint Committee on the National Transportation Communications for ITS Protocol in the US originally was formed to develop standard electronic protocol for traffic signals.

The committee, consisting of state and federal officials and representatives of trade associations including the American Association of State Highway and Transportation Officials, now is trying to produce a uniform communications protocol for RWIS.
5.12 The Next Generation RWIS

With the advances made in communications and technology (discussed above) it is apparent that significant improvements can and are being made to the provision of winter maintenance services. A reduction in operating costs is envisaged to be possible through the application of technologies such as GPS, GIS, database and web based services and new advances in remote measurement and modelling.

The RWIS currently in operation in the UK since the 1980s has provided highway engineers with reliable road weather forecasts for almost 20 years, and the system architecture provides the engineer with site specific forecasts for normally one sensor site in each climate domain. However, the engineer has to make use of the information from a number of disparate sources; including the sensors from the outstation, the weather forecast and the thermal maps to come to a decision about what action to take.

The next generation RWIS are applying some of the technological advances with a paradigm shift in the way in which road weather information is presented. An approach of providing forecasts on a route by route basis is being pioneered in the UK, in which the engineer is presented with an initial prediction as to which routes out of an authorities geographical area are likely to need treating, at what time treatment is required (based on when the road surface temperature is forecast to fall below zero) and the reason for action needing to be taken. This concept has been taken to the extent of providing a colour coded map of treatment routes based on the predicted action to be taken. The data from the disparate sources of sensors, weather forecast and road surveys are combined and the engineer has an intuitive easy to navigate user interface, whilst still being able to view the underlying data when required. The experience of the highway engineers can also be ‘built into’ the algorithms that are used.

Ideally this approach of route based forecasting is ‘driven’ by a weather forecast model which operates at a scale commiserate with the scale of the routes being managed. A relevant grid point, or combination of grid points, needs to be selected for each treatment route. By providing a site specific forecast for each of these points, the weather forecast provider will help ensure that the best possible forecast is made for each route. Where routes do not have an outstation present, the approach of using a virtual forecast site can be implemented. These virtual forecast sites are usually located at the coldest section/s of a given route to help ensure that the predicted action ultimately made for the route is the best possible. The data from surveys of the sky-view factor and other road data e.g. latitude, longitude, altitude, slope, aspect, road construction, thermal residual temperature, land use, cold air pooling index and traffic volume is used in the modelling process.

Route based forecasting takes a different approach to the traditional method of thermal mapping. Instead of being paper based and relying on the engineer to select the map most similar to the forecast conditions, route based forecasting makes use of a geographical database for each treatment route. A remote measurement survey is made around the route/s and the data is recorded into a database which continues to be used throughout the service provision rather than simply to construct a one-off map.

The next generation RWIS combines the weather forecast data with the microclimate of each treatment route to predict whether a given route needs treating. As such, the synthesis of geography and microclimate with weather forecasts enables each night is taken on its own merits, and there is no need to impose fixed climate domains and restrictive thermal map types. An energy balance model is run for numerous points around a route (typically every 20 metres, but decreasing to every 5 metres on bridges if required), and predicts the road surface temperature and condition at time periods of typically every hour, 30 minutes or even every 20 minutes.
A colour coded interface e.g. like traffic lights, with different colours representing different suggested actions provides the option to segregate between those routes definitely needing treatment, those which need to be monitored closely over a given night, and those not anticipated to need any treatment. The software is able to rank routes in a given authority area for a given night, such that it is immediately apparent to the engineer where their attention needs to be focussed. Such a ranking approach is important in that it is able to reflect the geography of each route as well as the predicted weather conditions on each night. Thresholds for the colour coding are agreed between the highway authority and the supplier and can be fine tuned over time using, even using a neural network embedded in the software to improve the suggested actions. Such solutions are hence dynamic in a way not seen before in the road weather market, and permit ongoing improvements whilst making best use of available technology. The next generation RWIS will in time lead to more uniform decision making across a region or country, and facilitate the sharing of information beyond the normal boundaries to enable an enhanced service to be provided, whereby updated information due to fast changing weather patterns could be incorporated into the RWIS rather than each authority effectively functioning independently.
Extension to The Footway

Historically the services dependent on RWIS have focussed on the road network, since it is here that the most profound effects of adverse weather occur. However, changes in the legal obligation of authorities in 2003 has meant that, in the UK, at least, authorities are responsible for ensuring safe passage along the footway.

Increasingly legislation is appearing (e.g. the Railways and Transport Safety Act 2003 in the UK) to require highway authorities conduct anti- and de-icing activities on footpaths and cycleways. Limited budgets mean that there is going to need to be some form of prioritisation in the footpaths to be treated. It is likely that this will be in part dependent on usage and access to public services, e.g. near schools and hospitals, as with roads, are likely to be a priority. There is an argument that heavily used pavements should be treated prior to ice forming or snow falling. For a proactive approach to occur requires accurate prediction of footway surface temperatures and conditions.

6 Bibliography

Key References


Shao, J., Swanson, J.C., Patterson, R., Lister, P.J. & McDonald, A.N. (1997) Variation of winter road surface temperature due to topography and application of thermal mapping. *Meteorological Applications* **4**:131-137


81


Tabony, R.C. (1985b) Relations between minimum temperature and topography in Great Britain. *Journal of Climatology* **5**:503-520


Thornes, J.E. (1985b) Thermal mapping, road danger warnings and ice on roads. *Proceedings of the 2nd International Road Weather Conference, Copenhagen, Denmark. SIRWEC*


