ROAD WEATHER INFORMATION SYSTEMS

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V.K. DRAVITZKI and C.R. VAROY
Opus Central Laboratories,
Lower Hutt, New Zealand

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PO Box 2331, Lambton Quay, Wellington, New Zealand
Telephone (04) 473-0220; Facsimile (04) 499-0733

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AN IMPORTANT NOTE FOR THE READER

The research detailed in this report was commissioned by Transit New Zealand when it had responsibility for funding roading in New Zealand. This is now the responsibility of Transfund New Zealand.

The material contained in this report is the output of research and should not be construed in any way as policy adopted by Transit New Zealand or Transfund New Zealand but may form the basis of future policy.

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EXECUTIVE SUMMARY

1. Introduction

This review of the international scientific and trade literature, undertaken in 1994, identifies the nature of road weather information systems (RWIS), their capabilities, the benefits arising from their use, and the costs associated with their installation and maintenance.

Complex nationwide networked RWIS now exist in many countries to advise road managers and motorists of extreme conditions, usually of ice, frost or snow but also of fog and high winds, on or near road surfaces. These are also relatively common hazards on many New Zealand roads.

RWIS typically monitor pavement and atmospheric weather conditions along traffic routes and provide early warning of hazardous conditions, often in advance of them being created, with significant benefits. For example, a system which predicts ice formation enables:

- Road users to be informed of hazardous conditions at an early stage so that re-routing decisions are made early and disruptions are minimised.
- Early initiation of winter maintenance procedures can be taken to restore safe driving conditions, for example snow ploughing, gritting, road closures or, as is common practice with Northern Hemisphere countries, the salting of the affected roads.
- Measures to mitigate the hazard can be optimised. For example, measures to prevent ice from forming are most effective if applied early.

The early and accurate detection of adverse conditions allows for both warning of the developing hazard to be signalled, and for the activation of maintenance systems to mitigate the hazard at the point at which it is most easily removed.

RWIS generally consist of:

- sensors to detect surface pavement and atmospheric weather conditions;
- thermal maps of the highway systems to identify problem areas;
- forecasting systems to predict the onset of adverse road surface and atmospheric weather conditions;
- communication systems.

Not all these features need be included in every RWIS. An RWIS may operate remotely, contain a few on-site sensors and simply activate a variable message sign to give drivers adequate and credible warning that ice, snow or flooding hazards exist on the road. Conversely, the RWIS may be complex and highly detailed, consisting of communications networks, remote roadside weather stations, ice prediction software and meteorological consultants, and be distributed in localised regions or countrywide.

2. Benefit:Cost Ratios for RWIS

The benefits of RWIS arise from: improved trafficability; reduced but more effective winter maintenance; a reduction of accidents caused by adverse weather and road surface conditions; reduced traffic delays; and reduced impacts on the environment as use of winter maintenance materials are minimal. In one study, savings in accident costs contributed 92% of the total cost savings. Benefits appear to be greater in countries with moderate rather than severe winters because, in severe conditions, ice and snow are more certain and fewer decisions and warnings are required.

The costs associated with RWIS are hardware, software and forecasting services. The cost of a simple road weather station depends on the complexity of the system chosen, but is of the order of $15,000 to $40,000 (New Zealand dollars as at 1994).

Benefit:cost ratios of 5:1 have been conservatively estimated for USA and Finland, but ratios up to 20:1 have been reported when detailed weather forecasts are able to be used with the RWIS.

3. RWIS in New Zealand

Because ice, frost, snow and wind are relatively common hazards on many New Zealand roads and RWIS systems could be expected to make a significant contribution to road safety.

The New Zealand climate is significantly different from those of countries currently using RWIS (mainly North European and North American). The literature was put into the New Zealand context by studying weather conditions and accident rates along two sections of state highway (SH) that are significantly affected by snow and ice during winter. The sections are on SH1, Waiouru to Tirau, and on SH73, Christchurch to Otira).

These road segments both experience delays to traffic and incidence of ice-related traffic accidents which could be better managed with information provided by RWIS. Prediction of ice-forming conditions on the high traffic volume SH1 would initiate early maintenance action to keep the road open for longer periods. Accurate warning of hazardous road conditions could help reduce the severity and relatively high cost of accidents in icy road conditions.

A simplistic estimate of the cost of ice-related vehicle accidents on these two highway segments is $2.8M per year.

4. Conclusions

RWIS are a useful tool for intelligent highway management and can make a significant contribution to road safety by triggering pre-emptive maintenance action and by producing more credible warnings of hazardous conditions, with a consequent reduction in accidents.

The evidence in the literature review is that road weather conditions can be effectively monitored and predicted at centralised locations remote from the highway.

At present there is minimal use of RWIS systems on the New Zealand highway network. The case studies of SH1 (Waiouru to Tirau) and SH73 (Christchurch to Otira) indicate that RWIS offer significant potential to reduce ice-related accident and maintenance costs with a highly favourable benefit:cost ratio.

5. Recommendations

Further research based on the results of this review, undertaken to better establish the application of RWIS in New Zealand, should include:

- Establishment of a methodology for estimating benefit:cost ratios for RWIS, which could be included in the Transit New Zealand 1991 Project Evaluation Manual.
- Investigation of the effectiveness of the pavement sensors when used in a chipseal type of road construction.
- Investigation of the ease with which systems and their particular communications protocols can be implemented in New Zealand.
- Investigation of the feasibility of New Zealand weather forecasters to provide local area forecast support for RWIS implementations.
- A more detailed review of specific systems which may be suitable in New Zealand, once specific potential sites and intended uses have been identified.
- The application of RWIS for roads affected by high winds and fog.

ABSTRACT

Ice, frost, snow, fog and high wind are relatively common hazards on many New Zealand roads, and road weather information systems (RWIS) could be expected to make a significant contribution to road safety.

A review of the international scientific and trade literature undertaken in 1994 identifies the nature of RWIS, their capabilities, the benefits arising from their use, and the costs associated with their installation and maintenance.

Potential application of RWIS for icy road conditions in New Zealand is considered by reviewing weather and traffic conditions, accident rates and winter maintenance operations on two segments of state highways that are subject to ice and snow.

1. INTRODUCTION

One of the goals of roading authorities worldwide is to maintain safe roads. The major weather hazards affecting traffic safety on roads are rain, snow, ice, fog and wind. The problems caused by any of these are intensified when they occur in combination, and/or in darkness. It is possible, using state-of-the-art technology, to monitor these and provide early warning of hazardous conditions (Perry and Symons 1991). The systems used by roading authorities to assist in managing the effects of weather on the road are known generally as Road Weather Information Systems (RWIS).

"Road weather information" is more than detailed information about weather along traffic routes. It includes specific information about the nature of the road surface conditions, which enables advance warning of specific hazardous conditions to be given, often in advance of them being created.

RWIS were initially developed in the United States (USA) as Runway Weather Information Systems which supplied aircraft runway surface data such as temperature, wetness and de-icing chemical concentration, because weather forecasts based on aviation reports did not include information concerning runway surface or pavement conditions. The use of this extra information in making decisions for road management became an obvious extension (Kelley 1990). The need for such a system has been highlighted in a German study (Better Roads 1991) which concluded that the accident rate is five times higher just before ice removal measures are implemented, than in the period just after. As well, the German study showed that a well-maintained road in winter can be less dangerous than a dry road in summer. The utility of such systems lies in the early provision of road weather information which allows road management decisions to be more effective both in terms of cost and public safety.

RWIS consist of sensors, software, communications systems and personnel, and may be modular or interconnected in comprehensive networks to supply relevant road "weather" and atmospheric weather data to motorists, road managers and meteorologists. The complexity of an RWIS will depend on the specific requirements of the authority having jurisdiction for the provision of these services.

Complex nationwide networked RWIS now exist in many countries to advise road managers and motorists of extreme conditions, typically of ice, frost or snow but also of fog and high winds, on or near road surfaces.

RWIS can be viewed as one element of an intelligent highway system in which the development of hazardous conditions is predicted, with significant benefits. For example, a system which predicts ice formation enables:

- Road users to be informed of hazardous conditions at an early stage so that re-routing decisions are made early and disruptions are minimised.
- Early initiation of winter maintenance procedures can be taken to restore safe driving conditions, for example snow ploughing, gritting, road closures or, as is common practice with Northern Hemisphere countries, the salting of the affected roads.
- Measures to mitigate the hazard can be optimised. For example, measures to prevent ice from forming are most effective if applied early.

The early and accurate detection of adverse conditions allows for both warning of the developing hazard to be signalled, and for the activation of maintenance systems to mitigate the hazard at the point at which it is most easily removed.

This review of the available international scientific literature and trade literature was begun in 1994. Although much of the literature reviewed for this report deals with systems for snow and ice control, systems for other adverse weather and road surface conditions are discussed briefly. Of the scientific literature, one of the more pertinent is a study of RWIS undertaken under the Strategic Highways Research Program (USA) Project SHRP-H-350 (Boselly et al. 1993).

As the climates of countries using RWIS (mainly North European and North American) are significantly different from that of New Zealand, the literature was put into the New Zealand context by reviewing the road weather conditions and maintenance practices on two sections of New Zealand state highway (SH1, Waiouru to Tirau, and SH73, Christchurch to Otira), and considering the relevance of RWIS to these highway sections.

2. INTERNATIONAL USE OF RWIS

RWIS are used in many countries, notably in North America, Western Europe and Japan, for ice and snow control. Table 1 (extracted from Thornes 1993) shows the distribution of such systems, the amount of thermal surveying completed, and if the systems are supported by a computer network. Sweden's system is an example of a nationwide network system.

Table 1. Countries with RWIS installations (from Thornes 1993).

Country	Thermal mapping (km)	No. of road weather stations	Computer weather networks
Europe:			
Austria	0	280	None
Belgium	0	0	None
Denmark	4,000	220	Yes
Finland	500	150	Yes
France	750	200	Yes
Germany	200	160	Yes
Holland	3,000	153	Yes
Italy	0	30	None
Luxembourg	200	20	None
Norway	3,500	50	Yes
Spain	0	0	None
Sweden	12,000	550	Yes
Switzerland	100	200	Yes
United Kingdom	38,000	520	Yes
North America:			
USA	1,000	350	Yes
Canada	400	10	Yes
Others:			
Japan	70	2	None
Totals	63,720	2,895	–

The countries which use RWIS have generally high traffic volumes carried on dense highway networks and roads which are affected by snow and ice. Winter maintenance in those countries listed in Table 1 often involves the use of de-icing salts to facilitate snow and ice removal. Large quantities of de-icing salts are applied annually in Europe and North America, costing at least NZ$6 Billion (Thornes 1988). (Salt (NaCl) as a de-icing agent is at present not used in New Zealand, and a resource consent would be required for any area where it was proposed to be used)

The literature recommends the use of RWIS as a worthwhile measure for the reduction of both winter maintenance costs and the hidden social costs (Perry and Symons 1991, Ridley 1987, Boselly et al. 1993, Thornes 1988, 1993, Pilli-Sihvola et al. 1993). However, some early problems were encountered, especially in the initial development stages of the technology: notably lack of ruggedness; poor reliability; unsuitability for the highway environment; and poor performance (Ridley 1987).

RWIS are mainly used to manage roads where the skid resistance is affected by snow and ice. The systems assist the efficient utilisation of resources for snow and ice control and in providing early warning of hazards to motorists.

The benefits accrue when:

- roads are not treated unnecessarily (i.e. salting or gritting is not carried out on a road which does not freeze);
- treatment is applied to roads which indeed need treatment;
- treatment is applied at the right time (e.g. application of de-icing agents before freezing occurs leads to a marked reduction in the amount of the agent required (Better Roads 1991));
- warnings resulting from RWIS input are conveyed to motorists (accurate warnings will have the greatest effect on motorist behaviour).

It has been established (Jenkins and Cole 1986) that to be effective the information displayed by a traffic control device must be:

- conspicuous
- legible
- understood
- credible.

RWIS linked to active signs that indicate the hazard only when it is present greatly improve the credibility of those signs.

Less frequently used than for ice control, RWIS to detect and warn of high winds have been implemented. A notable example of a system for warning of high wind is installed on the Severn Bridge (England). Winds at the centre of the bridge span can be up to 1.5 times those at its abutments, and have been found to be hazardous to high-sided trucks and even to cars. Traffic management and operational guidelines have been developed (Perry and Symons 1991). Depending on measured and predicted wind speed and direction, options include: lane closures; lower vehicle speed limits; closure to high-sided vehicles; and complete closure.

RWIS can also be used to warn of fog, which is defined as atmospheric obscurity in which visibility is reduced to less than 1 km (caused by water droplets or particles). Thick fog results in visibility distances of 40-200 m, while dense fog results in visibility distances of 0-40 m. Perry and Symons note that little can be done to disperse fog when it forms, but its presence is strongly associated with increased accidents. Assessment of likely fog hazard can be done for new roads with a view to selecting a route having low fog hazard.

Instruments can sense visibility distances and activate warning signs. The UK Department of Transport (DOT) has installed sensors at 30 fog-prone sites on the M25 around London. These activate warning signals when visibility falls below 300 m.

3. FEATURES OF RWIS

RWIS may range from a minimal stand-alone remote installation to complex nationwide networks. The underlying principles of early warning of adverse road conditions, and possible early initiation of remedial work, are common to all installations. Systems for ice control are most common, and are described below. However, systems for other road weather conditions use similar sensors but require different interpretation of the information provided by them.

RWIS generally consist of:

- sensors to detect surface pavement and atmospheric weather conditions;
- thermal maps of the highway systems to identify problem areas;
- forecasting systems to predict the onset of adverse road surface and atmospheric weather conditions;
- communication systems, highway maintenance systems and maintenance plans.

Not all the above features need be included in every RWIS. An RWIS may operate remotely, contain a few on-site sensors and simply activate a variable message sign to give drivers adequate and credible warning that ice, snow or flooding hazards exist on the road. Conversely, the RWIS may be complex and highly detailed, consisting of communications networks, remote roadside weather stations, ice prediction software and meteorological consultants, and may be distributed in localised regions or countrywide.

3.1 Road and Atmospheric Sensors

Road sensors monitor the pavement surface temperature, the pavement subgrade temperature, and the presence of moisture and its physical state on the pavement. The surface and subgrade temperatures provide information about the direction of the surface heat flux, and enable ice formation to be predicted.

A state-of-the-art pavement condition sensor unit can be used to monitor up to seven definable states of surface moisture of the road, as well as the relative concentration of de-icing chemicals on the road surface. The seven surface states which can be measured are: white ice; black ice; snow; frost; dew; wetness; dryness.

Road sensors are of three types:

- *Active road sensors* which require an energy supply to heat or cool the sensor relative to the pavement surface. The probability of ice formation is predicted by cooling the sensor while monitoring road temperature. Ice or snow is detected by heating the sensor, and detecting any water which is produced by melting. They are also used to measure surface moisture and residual de-icing salts.

- *Passive road sensors* which measure the same properties as active sensors but do not require any energy input as they do not heat or cool the sensor relative to the pavement surface.

- *Non-contact road sensors* which are mounted on roadside poles and may use microwave or infrared sensing equipment. Such sensors scan and average over a much larger area of a road surface than that monitored by an in-pavement sensor. Potentially they can provide information that is more representative of pavement temperature and ice or moisture levels. They are relatively expensive at present and quite new to this field.

Road sensors are known to be reliable for temperature measurement, but are less reliable for measurements of surface moisture and residual de-icing salt (Perry and Symons 1991). Problems occur in the measurement of residual de-icing salt and surface moisture:

- when the surface of the road is dry and residual de-icing salt cannot be detected (this is usually measured by electrical conductivity, which requires moisture to be present);

- when hygroscopic de-icing salts are used, which make the sensor surface wet while the road surface is dry.

These problems can be overcome by a knowledge of local (roadside) weather conditions and reference to previous residual chemical readings from the same sensor data.

Atmospheric sensors may be multipurpose or stand-alone units. They provide data on air temperature, dew point, wind speed and direction, and precipitation. This data, combined with data from road sensors, can be used to predict which of the road surface states is likely to occur.

These sensors are typically: standard anemometers; vanes; relative humidity and temperature sensors, and are readily available from manufacturers. Other atmospheric sensors which may be incorporated into RWIS include precipitation (amount and type) sensors and visibility sensors.

Road and atmospheric sensors have three functions:

- to provide data to forecast hazardous conditions, which allows maintenance to be initiated or maintenance crews to be put on standby before the road surface conditions actually occur;
- to monitor current conditions, i.e. to follow trends and analyse the accuracy of forecasts;
- to detect critical thresholds which require action by the road manager.

The number and placement of sensors required for an RWIS are determined by the use to which the system will be put. A typical installation consists of atmospheric sensors located so that they can determine local weather conditions adequately, and a number of road sensors. Access to either mains or solar power and possibly telephone lines needs to be considered in placing these sensors. Battery-powered sensor systems with satellite communications are likely in the future (Perry and Symons 1991).

Boselly et al. (1993) suggest locating road sensors, as in Table 2, which illustrates that sensor placement needs to also consider the interaction of traffic with the road surface. In this table, "outbound" refers to traffic direction on a highway away from a major urban centre, "inbound" refers to the direction towards the urban centre, and "through" lane is defined to distinguish the passing lane from other lanes on multi-lane roads.

Table 2. Suggested locations for pavement sensors in roadways (Table 2-2 from Boselly et al. 1993).

Primary use of sensors	**Location of road sensors within lanes**			
	Urban (commuter route)		**Rural (non-commuter route)**	
	Multi-lane road	**Two-lane road**	**Multi-lane road**	**Two-lane road**
Prediction	Just outside an outside wheeltrack of outbound passing lane	Just outside an outside wheeltrack of outbound lane	Just outside a wheeltrack of a passing lane	Just outside a wheeltrack of either lane
Detection	Just inside an outside wheeltrack of inbound through lane	Just inside an outside wheeltrack of inbound lane	Just outside a wheeltrack of a through lane	Just outside a wheeltrack of either lane
Monitoring	Use the suggestions for prediction placement (above) whenever possible			

The use of the outbound direction for prediction and the inbound direction for detection is not directly explained by the authors, but probably refers to traffic levels at times when ice is most likely to form. For instance, the early morning hours are a common time for heavy inbound traffic. Heavy traffic on a predictive location would tend to raise road temperatures near the sensor, and thereby interfere with the prediction process. Thus the prediction may be for no ice formation yet ice may be forming at other positions on the road.

The accuracy of the temperature measurement by the sensors is highlighted in the literature (Boselly et al. 1993, Perry and Symons 1991). Clearly any RWIS should incorporate a programme to maintain the sensor calibrations. Perry and Symons (1991) mention automatic self-calibration for temperature sensors and predict that all sensors will eventually have this facility. Minimum standards for sensor accuracy are already in place in the UK (UK DOT 1988).

3.2 Thermal Mapping

Thermal mapping provides information about the time and spatial variations of the road surface temperature which can be used to infer moisture/ice levels for a given road network.

The terminology is defined from Perry and Symons (1991) as follows:

- *Thermal mapping:* the measurement of spatial variation of road surface temperature along a road, using an infrared thermometer or camera.
- *Thermal fingerprint:* the graphical representation of temperature against distance for a particular route on a given night.
- *Thermal map:* the representation on a road map of the average spatial variation of minimum road surface temperature for different weather conditions.

Thermal mapping is used to identify suitable sites for pavement sensors, and to enable data from pavement sensors to be extrapolated to other locations. The current view of the utility of thermal mapping appears to be that of Harverson (1990): *"it is a useful but not essential addition to an ice warning system"*.

Thermal mapping is carried out at night because, for most of the night, there is little temperature variation. Temperatures drop rapidly after sunset but then fall more gradually to a minimum near dawn. In the hours before dawn the temperatures are quite stable. Thermal mapping enables sensors to be sited at critical (e.g. minimum temperature) points. These sensors provide reference absolute temperatures with which to set the scale of the relative temperatures of the thermal map.

In the USA, thermal mapping has also been used to establish the most efficient snow plough routes and to develop a staged response to snow and ice control (Boselly et al. 1993). In the UK it has been used to improve effectiveness of gritting operations (Skinner 1993, Stannard 1992, McDonald and Lister 1990, Municipal Journal 1986).

Because thermal maps would be impractical to provide for all weather conditions, they are produced only for weather scenarios that will most likely result in ice formation. Meteorological training may be required to choose the thermal map that is most appropriate to the weather condition being experienced, and to decide its appropriateness as a predictive tool.

The most significant weather condition is the clear, calm night in winter when cooling by radiation of the road surface is greatest, and results in low pavement temperatures. Surface temperature variations are then at their maximum, with the lowest temperatures occurring in valleys and other low spots where cool air may pool, and the warmest are at higher altitudes. This condition is typical of a "temperature inversion", which is a reversal of the normal tendency for temperature to decrease with altitude.

Where cloud cover exists, the surface radiation is reflected and/or absorbed, and re-emitted to the road surface, thereby reducing cooling by radiation. In such a case the road surface temperatures tend to parallel the normal trend with warm temperatures at low elevations and cool at high elevations. Similarly, wind on clear nights tends to reduce the effects of cooling by radiation because it mixes warmer upper air layers with the cooler air at lower elevations.

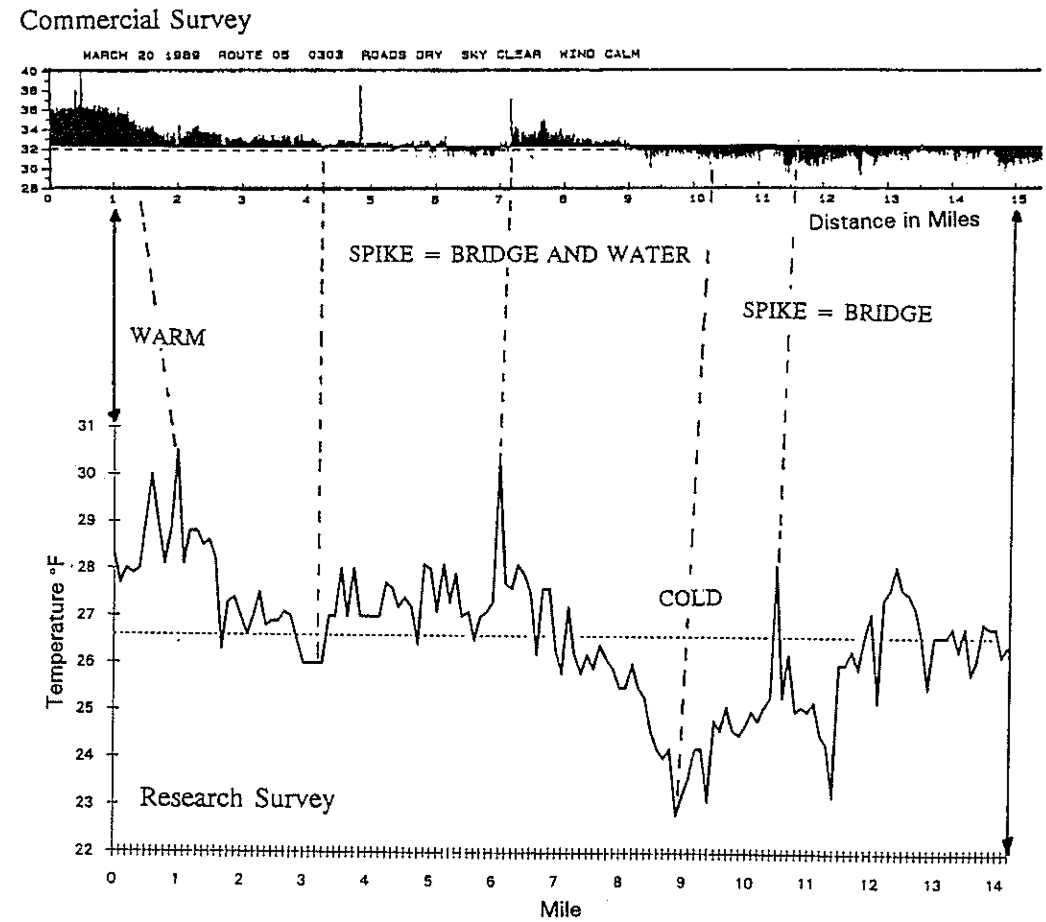
Variations of these conditions are used to define three convenient classifications of thermal fingerprint, namely extreme, intermediate and damped:

- *Extreme thermal fingerprints* represent the conditions occurring on clear, calm nights during anticyclonic weather when frost may form on roads.
- *Damped thermal fingerprints* represent the conditions occurring during cyclonic weather (typically overcast, rainy and windy), when spatial temperature variations are reduced.
- *Intermediate thermal fingerprints* fall between the extreme and damped limits, and occur most often.

An example of a thermal fingerprint taken from Boselly et al. (1993) is displayed in Figure 1.

The choice of the weather condition for which thermal mapping is performed is usually influenced by meteorological advice, financial considerations, and the perceived usefulness of the data. Thermal mapping for five different conditions is common in the UK, and the UK DOT requires that thermal mapping is carried out in at least three of the weather conditions outlined above (Harverson 1990).

Figure 1. Two examples of (commercial and research) thermal analysis of highway temperature. (Figure 2-15 in Boselly et al. 1993).



3.3 Climate Mapping

Climate mapping is an extension of thermal mapping and takes into account the local microclimate, vegetation and topology with the thermal map, and is intended to produce improved local predictions.

Microclimate is the result of the interaction on the small scale of the weather and local topographical features. Climate mapping assists in the analysis of information fed back from a field station and serves to minimise the number of field stations required for a network. At present in New Zealand, climate mapping is done in an informal manner by the maintenance contractor, using their knowledge of problem areas.

A climate map produces three outputs:

- optimised locations and minimised number of field stations and pavement sensors;
- thermal maps of road surfaces;

- microclimate analysis highlighting unusual features and potentially hazardous winter road conditions.

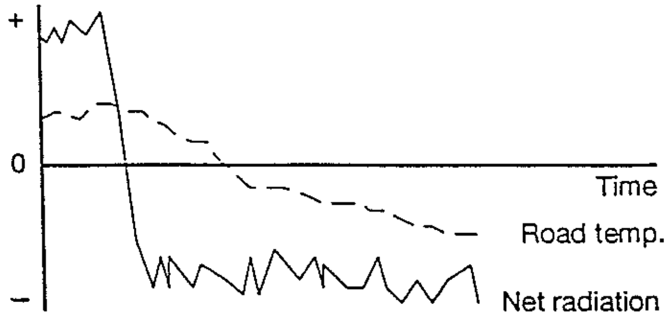
3.4 Road Weather Forecasts and Ice Prediction

Road weather forecasts are prepared from both observations and forecasts. They are further divided according to road and synoptic (i.e. based on the overall weather pattern) weather information. The forecast is based on meteorological data such as cloud cover, weather type, air temperature, relative humidity, wind speed and direction, and on weather radar and satellite images. These forecasts may be made more site-specific by using enhanced forecasting services. These are sometimes called Value Added Meterological Services (VAMS) in the USA.

Models to predict the onset of ice have developed markedly in the UK, Sweden, France, the USA and Finland in the last 20 years. The literature obtained for this report deals mainly with the two UK models and identified the Vaisala Icebreak model as the best performer (Shao et al. 1991). This result is based on a comparison of the models' outputs with on-site records of ice/frost occurrence. Comparative studies for other ice prediction software were not found in the literature..

The potential of ice prediction is illustrated by Figure 2, taken from the 1994 trade literature provided by Anderaa Instruments. The two lines in the graph show the variation with time of readings from a road temperature sensor and an aboveground net radiation sensor. The downwards trend of the road temperature towards 0 °C can be used to predict a frost if road surface moisture is present or atmospheric relative humidity allows moisture precipitation onto the road. However, the major transition of the net radiation from a road thermal gain through zero to a road thermal loss occurs much earlier, at a time when the change in road temperature data is still not distinguishable from the typical variations seen earlier. The net radiation data can therefore be used to predict ice formation earlier than with road sensor temperature data alone.

Figure 2. Temperature and radiation flux measurements from an RWIS (reproduced from 1994 trade literature of Anderaa Instruments).



RWIS must provide a prediction several hours ahead of the time that ice will form if maintenance operations are to be deployed to treat the icing at the most efficacious time. This prediction must be reliable (Perry and Symons 1991) as:

- failing to providing a warning when ice does occur does nothing to mitigate the hazard and creates a false sense of confidence;
- false warning of ice when ice does not form reduces the credibility of the system to drivers and initiates unnecessary remedial action (salting or gritting).

Ice prediction models have advanced to the stage where road surface temperature predictions may be considered accurate to ±1 °C 90% of the time, giving 8-24 hours advance warning (Thornes 1989, Thornes and Shao 1991, Shao et al. 1993).

3.5 Presentation of Warnings

The manner in which warnings are presented to motorists is particularly important if they are to be credible and effective. Fixed signs warn of a weather hazard even when it is not present, and it is left to the motorist to assess whether the hazard is real or not. Changeable (or variable) message signs (CMS or VMS) actuated as a result of RWIS forecasts remove this assessment from the motorist and they perform well (Pouliot and Wilson 1993).

The significance of warnings will also be enhanced if the message can be reinforced by other means such as the media (radio, TV or newspaper for longer range forecasts) or Meteorological Office forecasts. A new development called Radio Data Service (RDS) uses FM radio to convey weather information or road hazard warnings to motorists. The key element of this technique is that it uses part of the FM radio frequency bandwidth already allocated to radio stations. Because FM stations do not use the whole of the bandwidth for their broadcasts, the unused part of the bandwidth can be licensed (rented) to enable other information to be transmitted concurrently with, and at the same nominal frequency as, the station broadcast. RDS-equipped receivers are expected to become a commonplace technology in the near future.

3.6 Computer and Communication Networking

For a networked RWIS, remote road and meteorological sensor information needs to be combined with weather information from other sources. Potential system communication problems will occur if the system components from different manufacturers and/or countries do not adhere to standard communication protocols. Despite these potential problems, networked systems appear to be functioning well in several countries, for example Sweden and Finland.

4. BENEFIT:COST RATIOS FOR RWIS

The increasing use of RWIS overseas suggests that real cost savings and improved levels of service benefits accrue. Well-planned installations can have a short payback time (Harverson 1986, Stannard 1992, McDonald and Lister 1990, Better Roads 1991).

The real benefits are derived from: improved trafficability; reduced but more effective winter maintenance; a reduction of accidents that are caused by adverse weather and road surface conditions; reduced traffic delays; and reduced impacts on the environment because use of winter maintenance materials is minimal (mainly Northern Hemisphere) (Ridley 1987, Perry and Symons 1991). The costs associated with RWIS are hardware, software and (road and synoptic) forecasting services.

Pilli-Sihvola et al. (1993) claim that improvement in maintenance activities such as starting to salt roads 50% earlier decreases accidents by 3-17%, depending on the district and the winter.

They calculate the benefits as cost savings in three categories: cost of accidents, time costs and vehicle costs. For the Kymi road district, a typical road district in Finland (Pilli-Sihvola et al. 1993), the contribution of each category to the benefits was heavily weighted towards the accident costs. The relative contributions were accident 92%, time 6% and vehicle costs 2%.

The cost of an RWIS system is dependent on the size and complexity of the chosen system. Anderaa Instruments estimate the cost of a typical single weather station with communication system in the range US$10,000 to US$15,000 f.o.b. (free on board). Boselly (1993) puts the cost of a single RWIS outstation with pavement and meteorological sensors at US$20,000 to US$40,000.

Estimates of the benefit:cost ratio of RWIS range from –1.5 to a value between 10 and 20. The value depends on the form of the RWIS implementation and the factors accounted for by the calculation (Jonas 1991, Boselly 1992, 1993, Pilli-Sihvola et al. 1993, Thornes 1993).

Pilli-Sihvola et al. (1993) estimate a benefit:cost ratio of 5:1 for a typical road district in Finland. Thornes (1993) mentions the same 5:1 ratio being referred to in an earlier research program "Storm Monitoring / Communications" (SHRP-87-H-207). The recommendation of that report was that *"state highway authorities with an annual budget of more than US$1 million (for winter ice control) should investigate the possibility of using RWIS for snow and ice control"*. The report states that RWIS which combined sensor input and road thermography into detailed road weather forecasts, tailored to the needs of snow and ice control managers, offers the opportunity for a significant return of the investment at a benefit:cost ratio close to 5, with a significantly improved level of service on the roads and greatly decreased frequency of decision errors (see also Boselly 1992, Boselly et al. 1993, Jonas 1991).

Boselly (1993) looked at a subjective level of service and the benefit:cost ratio in his benefit:cost model analyses. One of these analyses produced a benefit:cost ratio of about 20 when road maintenance decisions were made with detailed forecast (VAMS) support compared to decisions made with no support. Detailed forecast alone has the greatest effect of the benefit:cost ratio. Accurate forecasts reduce bad maintenance decisions.

5. SUPPLIERS OF RWIS EQUIPMENT

As yet, little of the published literature is concerned with the relative effectiveness of the range of components supplied by the different manufacturers.

A search of trade sources was made to identify suppliers of RWIS equipment. The major differences between manufacturers' systems appear to be in: communication protocols; pavement sensor implementation; and ice prediction software.

A list of the identified equipment manufacturers and a brief outline of their products, if available, is shown in Table 3.

Table 3. Equipment manufacturers of RWIS and their products identified in a search of trade sources.

Manufacturer	Country	Products
Climatronics	USA	Complete RWIS, climate and thermal mapping
Vaisala	Australia, USA, Europe	Complete RWIS, climate and thermal mapping
Boschung Mecatronic	Switzerland	Complete RWIS, thermal mapping
Telub AB	Sweden	Complete RWIS, climate and thermal mapping
Anderaa Instruments	Norway	Complete RWIS
Surface Systems Inc.	USA	Complete RWIS, climate and thermal mapping
Findlay, Irvine	Scotland, USA	Complete RWIS, thermal mapping

More detailed information on the components with the suppliers' range of equipment is given in Table 4.

Table 4. Equipment manufacturers of RWIS and details of components they can supply.

Manufacturer	RWIS	Ice prediction software	Climate/thermal mapping	Pavement sensor	No. of conditions detected[1]	Meteorological sensors (standard[2])	No. of sensors per out-station
Climatronics	✓	✓	✓	Active	4	✓	30
Vaisala	✓	✓	✓	Passive	7	✓	Not known[3]
Boschung Mecatronic	✓	✓	✓	Not known[3]	Not known[3]	✓	Not known[3]
Telub AB	✓	✓	✓	Not known[3]	Not known[3]	✓	Not known[3]
Anderaa Instruments	✓	Not known	x	Active	Not known[3]	✓	Not known[3]
Surface Systems Inc.	✓	✓	✓	Active	5 + solution depth, % ice in solution	✓	Not known[3]
Findlay, Irvine	✓	✓	✓	Active	Not known[3]	✓	80

1 These may include any of the seven definable road surface states listed in Section 3.1 in this report.
2 The standard meteorological sensors include those for wind speed and direction, air temperature, relative humidity, visibility, precipitation.
3 Not known, i.e. not indicated on manufacturer's datasheets.

6. RWIS IN NEW ZEALAND

Currently the predominant means of warning about hazardous road conditions in New Zealand are fixed signs, although illuminated signs which rely on input from a road sensor are deployed at a small number of sites. These systems are minimal and consist essentially of a thermocouple buried near the road surface which remotely activates an ice warning sign. They do not predict ice conditions, but simply indicate that the temperature is low enough for ice to form.

Technology has reached a stage where, based on international evidence, the monitoring equipment needed for such advanced warning systems is economically priced. Ice, frost, snow and wind are relatively common hazards on many New Zealand roads and these RWIS systems could be expected to make a significant contribution to road safety. A review of the systems currently available, and of their capability, their appropriateness in New Zealand conditions, and their cost of installation and maintenance is therefore timely.

6.1 Case Studies of Road Weather Conditions in New Zealand

Weather conditions and accident rates along two sections of the national state highway network, that are significantly affected by snow and ice during winter, were investigated as case studies to identify the potential for application of RWIS in New Zealand.

These sections of state highway were SH1 from Waiouru to Tirau, important as a national arterial route, and SH73 from Christchurch to Otira, an important communication and tourism link. The traffic volume data for these sections of highway were obtained from the Transit New Zealand (1993) publication "Traffic Volumes".

Weather information up to 1980 was obtained from the literature (New Zealand Meteorological Service 1983) and from updated information obtained from National Institute of Water and Atmospheric Research Ltd (NIWAR) (Mr Stuart Burgess, pers.comm.). On parts of the highway without a nearby weather station, the nearest weather station at a similar altitude was selected for its data. This approach, recommended by NIWAR, is intended to provide the most representative data for the chosen highway sections.

Accident statistics for 1984-1993, for three categories of accident (fatal, serious and minor) and for the three road surface conditions (dry, wet and icy) were obtained from the Land Transport Safety Authority (LTSA). The summarised data are presented in Table 5, and include all road sections between the road reference stations closest to the starting and end points of the chosen stretches of highway. These data do not include non-injury accidents before 1989.

Table 5. Weather-related accidents that occurred on sections of SH1 and SH73 during the time period 1984-1993.

Location/ reference station numbers	Time period	Condition				Ice-related accident injury severity			
		Dry	Wet	Icy	Total	Fatal	Serious	Minor	Non-injury
SH 1/ 0518-0728	Total period (10 years)	871	536	40	1360	7	11	28	16
	Annual average	87	54	4	N/A	N/A	N/A	N/A	N/A
SH 73/ 0000-0159	Total period (10 years)	1001	274	29	1303	0	6	22	13
	Annual average	100	27	3	N/A	N/A	N/A	N/A	N/A

N/A not appropriate.

Data obtained on maintenance performed and road closure actions for SH73 (1992 to 1994), and for SH1 (1986 to 1993) are shown in Table 6.

Table 6. Closures and ice gritting performed on SH1 and SH73.

Road	Road Closures (Partial closures, i.e. chains required)								SH 1 Ice gritting (average lane km/ year)
	1986	1987	1988	1989	1990	1991	1992	1993	
SH 1 Desert Road	6	2	5	7	9	13	20	9	40
SH 1 Turangi-Atiamuri									10
SH 1 Atiamuri-Tokoroa									10
SH 73 Arthur's Pass							6 (19)	1 (10)	
SH 73 Porters Pass							4 (13)	0 (9)	
SH 73 Ice gritting (actual lane km/year)							248	375	

6.1.1 State Highway 1, Waiouru to Tirau

The length of highway covered is 208.6 km of SH1. Volumes of 4,000-6,000 vehicles per day (vpd), rising to about 15,000 vpd at major townships are typical.

The weather data for SH1 are shown in Table 7. As well as listing data for Waiouru (823 m), data for Turoa (altitude 1628 m) are included because its snow-lying data are expected to be more representative of the Desert Road conditions (NIWAR, Mr Stuart Burgess, pers.comm.). The data relate to off-road sites so should be treated with circumspection as it is not clear how road surface temperatures correlate with off-road ground temperatures.

Frost could be expected on roads for part of the day on approximately 70-100 days a year. Snow occurrence and snow lying became more significant at the higher altitudes of the Desert Road (above approximately 800 m). Over an 8-year period (1986-93) the Desert Road was closed on average 9 times per year. The amount of gritting carried out on SH1 is about 60 lane kilometres per year.

Ice was reported to have been a factor in 2.85% of all accidents. The data show that accidents in icy conditions are likely to be serious or fatal. Using LTSA social cost valuations of accidents ($2.6M for fatal, $460,000 for serious injuries, and $58,000 for minor injuries), the cost of these accidents in icy conditions can be estimated to be $24.88M over a 10-year period.

6.1.2 State Highway 73, Christchurch to Otira

The length of highway studied is 167.4 km or 72% of SH73. Traffic volumes of SH73 are about 28,000 per day in urban portions of Christchurch, decreasing to about 2,000 at 25 km from central Christchurch, and to 900 per day from Darfield onwards.

The weather data for SH73 are shown in Table 7. Data from Craigieburn (altitude 914 m) and Lake Coleridge (364 m) are included as representative of Porters Pass (914 m) and the mid-altitude of this section of SH73 respectively.

Frost could be expected on roads for part of the day on approximately 80-140 days a year. Snow occurrence and snow lying became more significant at the higher altitudes west of Darfield (above approximately 300 m). For the 2-year period 1992-93, Arthur's Pass (altitude 924 m) was closed to vehicles without chains (i.e. partial closures) on average 15 times per year, while Porters Pass was closed 11 times per year. These passes were closed completely three and two times per year (average) respectively. The amount of gritting on SH73 has been about 250 lane kilometres per year.

Ice was reported to have been a factor in 2.2% of all accidents. The data show that, compared with SH1, accidents in icy conditions are less likely to be serious or fatal. Using the LTSA social cost valuations of accidents, the cost of these accidents in icy conditions can be estimated to be $4.04M over a 10-year period.

Table 7. Total days per year of ground frost, snow occurrence, snow lying, and annual average daily traffic volume (AADT).

Highway	Location (altitude m)	Total days ground frost/yr	Averaging period	Total days snow occurrence/yr	Total days snow lying/yr	Approximate traffic volume (AADT)
State Highway 1	Tokoroa (305)	79.7	1973-1981	0	0	6,385
	Atiamuri (253)	49.7	1967-1989	0	0.1 (1972-1989)	6,400
	Wairakei (402)	124.7	1962-1987	0.4 (1963-1987)	0.1 (1972-1987)	6,400
	Taupo NZED (376)	69.9	1950-1994	0.1 (1950-1991)	0.2 (1972-1991)	6,400
	Turangi (366)	76.5	1968-1993	1.4 (1968-1972)	N/A*	4,200
	Turoa Ski Field (1628)	N/A	1978-1979	61.7	73.5	not on highway
	Waiouru (823)	100.9	1966-1988	18.3	12.7	3,000
State Highway 73	Christchurch Airport (30)	88.4	1953-1994	0.5 (1972-1991)	2.7 (1993-1994)	25,000
	Darfield (195)	102.6	1944-1994	4.2 (1939-1991)	4.0 (1972-1991)	900
	Lake Coleridge (364)	123.8	1917-1980	9.3 (1928-1976)	1.0 (1972-1976)	not on highway
	Craigieburn (914)	145.1	1964-1994	38.2 (1964-1986)	39.1 (1972-1986)	not on highway
	Otira (383)	78.2	1973-1987	N/A	N/A	800

* N/A not available.
(19..-19..) Years in columns 5 and 6 indicate years over which averaging has been made when this is a different period than is shown in column 4.

6.2 Benefits of Using RWIS in New Zealand

The above data suggest that benefits would accrue from the installation of RWIS. Possible benefits include more efficient gritting operations, reductions in frequency and possibly in severity of injuries in accidents, and financial benefits from improved flow of traffic by re-routing.

The road segments used for the two case studies both experience delays to traffic and an incidence of ice-related traffic accidents which could be better managed with information provided by RWIS. Prediction of ice-forming conditions on the high traffic volume SH1 would initiate early maintenance action to keep the road open for longer periods. Accurate warning of hazardous road conditions could help reduce the severity and relatively high cost of accidents in the icy road conditions.

A simplistic estimate of the cost of ice-related vehicle accidents on these two highway segments is $2.8M per year. As discussed in Section 4 of this report, accident-cost reduction is the major contributor to the benefits of using RWIS.

6.3 Implementation of RWIS in New Zealand

Significant technical issues are likely to be encountered when implementing a networked RWIS in New Zealand. These relate particularly to: the compatibility of the equipment from different manufacturers when installed in a common system; communications protocols; and ability to be connected to the telephone network. The impact of these issues, and how they could be overcome, would need to be considered in the context of a particular proposed installation.

A clearly defined communication protocol has been developed in the UK to enable weather offices to communicate with any commercially available sensor system (Perry and Symons 1991). The feasibility of such a protocol in New Zealand has not yet been investigated.

The benefit that can be achieved using RWIS in New Zealand is possibly even greater than that achieved overseas because the weather and the maintenance strategies in New Zealand differ considerably from those of USA and Europe. New Zealand tends to have winters with road temperatures often fluctuating around 0°C. At this temperature range, not only is skid resistance least, but motorist appreciation that a hazard may exist is low. In contrast, the severe winters in the USA and Europe mean that the temperatures are likely to be below 0°C for long periods. Skid resistance is slightly higher on the hard ice at these low temperatures but, more significantly, appreciation of the hazardous conditions is much higher. This means that decisions on whether or not to begin gritting the roads need to be made more often in New Zealand than in the USA or Europe, where salting and gritting operations are of a more routine nature. Indications are that benefit:cost ratios are less for countries with more severe winters because fewer decisions need be made. Therefore RWIS installations in New Zealand could produce a relatively high benefit:cost ratio (i.e. greater than 5:1), but further research is needed to confirm this.

The use of sensors in pavements of chipseal construction needs to be considered. These sensors, which need to be securely fitted in the road, are quite large and are influenced by the thermal mass of the surrounding pavement. While embedding them in a bituminous grout will secure them in the road, this may result in the sensor not measuring the thermal behaviour of the pavement accurately. The significance of this should be established.

RWIS for wind is a further potential use for these systems in New Zealand. New Zealand has a number of locations where road sections are exposed to strong wind gusts. Control by passive signs tends to be only a crude measure, and a warning sign linked to RWIS would be more positive and credible.

There are road sections affected by fog, e.g. SH1 near the Waikato River, for which RWIS systems could be further investigated. Sensors which detect reduced visibility can activate warning messages for motorists. This is of particular application to two-lane roads with opposing flows on which, in foggy conditions, overtaking margins may be less than they appear.

7. CONCLUSIONS

This review demonstrates that RWIS are a useful tool for intelligent highway management. RWIS can make a significant contribution to road safety by triggering pre-emptive maintenance action and by producing more credible warnings of hazardous conditions with a consequent reduction in accidents.

The evidence in the literature review is that road weather conditions can be effectively monitored and predicted at centralised locations remote from the highway.

At present there is minimal use of RWIS systems on the New Zealand highway network. The case studies of SH1 (Waiouru to Tirau) and SH73 (Christchurch to Otira) indicate that RWIS offer significant potential to reduce ice-related accident and maintenance costs with a highly favourable benefit:cost ratio.

8. RECOMMENDATIONS

As a result of the review, further research undertaken to better establish the application of RWIS in New Zealand should include:

- Establishment of a methodology for estimating benefit:cost ratios for RWIS which could be included in the Transit New Zealand (1991) Project Evaluation Manual.

- Investigation of the effectiveness of the pavement sensors when used in a chipseal type of road construction.

- Investigation of the ease with which systems and their particular communications protocols can be implemented in New Zealand.

- Investigation of the feasibility of New Zealand weather forecasters to provide local area forecast support for RWIS implementations.

- A more detailed review of specific systems which may be suitable in New Zealand once specific potential sites and intended uses have been identified.

- The application of RWIS for roads affected by high winds and fog.

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