NIGHT ICING POTENTIAL PREDICTION SYSTEM

P. Richard
Department of Transportation and Infrastructure Renewal
Halifax, Nova Scotia, Canada
richarpa@gov.ns.ca

P. J. Delannoy
AMEC Earth and Environmental
Ottawa, Ontario, Canada
paul.delannoy@amec.com

ABSTRACT

A cost-effective approach for the preparation of infra-red (IR) thermal fingerprints was devised by Nova Scotia Transportation and Infrastructure Renewal (NS TIR). NS TIR patrol vehicles, outfitted with an IR sensor and a GPS-based Automatic Vehicle Location (AVL) system were used to collect road temperature data. AMEC meteorologists coordinated the IR runs and then extracted and analysed the data against the weather conditions during the run. A set of three thermal fingerprints was successfully produced in a modern GIS (Geographic Information System) format.

Portions of TCH 104 were associated with one of the two Road Weather Information Systems (RWIS) along the route and the route divided into equal segments. An operational service, based on selecting the appropriate thermal fingerprint for the coming night's forecast weather, together with the forecast pavement and dew point temperatures for the associated RWIS, was devised to determine if there was a potential for the formation of frost on any segment of the roadway. The earliest time for the onset of frost formation in each segment is returned, plotted on a GIS map of the highway. Thus a simple graphical guidance product is made available to help maintenance supervisors deal with the potential of frost formation.

KEYWORDS

THERMAL MAPPING / FROST / ICING / PREDICTION / DECISION AID

1. INTRODUCTION

Thermal imaging of roadways using infra-red (IR) sensors has been used to quantitatively describe the thermal behaviour of an entire length of a roadway at night under a fixed number of identifiable weather conditions [1]. The diagrams produced, which are unique to each roadway, are generally referred to as thermal fingerprints. However, acquiring the IR data for the roadway is labour-intensive and therefore expensive.

In the last several decades, road agencies around the world have been deploying Road Weather Information Systems (RWIS) which monitor atmospheric and pavement conditions at a single point. Meteorological services are then retained for the preparation of forecasts of future road surface temperature and condition for the RWIS locations. These services perform very well today but are limited to the instrumented location. Thermal fingerprints provide a means of determining which road segments are colder or warmer than an associated RWIS site and can be used to forecast pavement temperatures along the entire length of the roadway at night. These products are particularly effective winter maintenance tools in moist winter climates where humidity is abundant and so frost will form the instant any portion of the roadway drops below freezing.

For cold, snowy winter climates, such as are found through most of southern Canada, the formation of frost on roadways presents a greater challenge. Road surface temperatures can be well below freezing the entire night along the full length of the roadway yet frost may form in some sections but not in others. To forecast where and when frost will form, if at all, one must determine where and when road surface temperatures will simultaneously drop below freezing and below the dew point temperature.

While snow fighting or snow clearing continues to be the dominant winter road maintenance concern across most of southern Canada, our recently warming climates may cause fundamental changes to winter weather. With milder and moister conditions becoming more common, the occurrence of frost on roads may increase. There is also evidence to suggest that the formation of frost on roads, quickly changed to ‘black ice’ by the action of traffic, is a particularly dangerous winter driving hazard [2]. It is very important therefore to have tools to deal effectively with this phenomenon.

Producing thermal fingerprints and thermal maps in the traditional manner, by contracting out the entire data acquisition activity, was generally considered prohibitively expensive in cold climates where the formation of frost on roadways is less prevalent and so the benefits to be gained smaller. More economical methods were required. In addition, the ultimate end use of these products in cold climates had never been advanced to the point of providing a simple, operational product to guide the decisions of road supervisors. Modern informatics tools can be effectively applied to determine precisely when and where there is a Night Icing Potential (NIP). This paper describes some new approaches.

2. COST-EFFECTIVE THERMAL FINGERPRINTS

Officials of the Nova Scotia Department of Transportation and Infrastructure Renewal (NS TIR) proposed to acquire all of the IR data themselves. A patrol vehicle, suitably equipped with a Sprague RoadWatch IR sensor and an Automatic Vehicle Location (AVL) unit, was already available as was contracted operator time. The AVL service collects vehicle location, speed, heading, and time information using the Global Position System (GPS) and provides this information back to NS TIR through the Internet. The IR sensor was connected directly into the AVL unit so that road surface and air temperatures from the RoadWatch unit were also automatically relayed. In this way NS TIR cost-effectively managed the full data acquisition portion of the thermal mapping process.

A section of Trans-Canada Highway (TCH) 104 in Pictou County, Nova Scotia, was selected for a demonstration project (Figure 1). The test length commenced just east of New Glasgow and ran 42 kilometres along TCH 104 to the Pictou County line. There are two RWIS sites along the route: Upper Mount Thom and Mount William Road. The terrain varies significantly along the route from near sea level around New Glasgow to elevations approaching 250 metres above sea level in the Mount Thom area. Mount Thom is known to be particularly prone to dangerous driving conditions due to local weather and elevation effects.

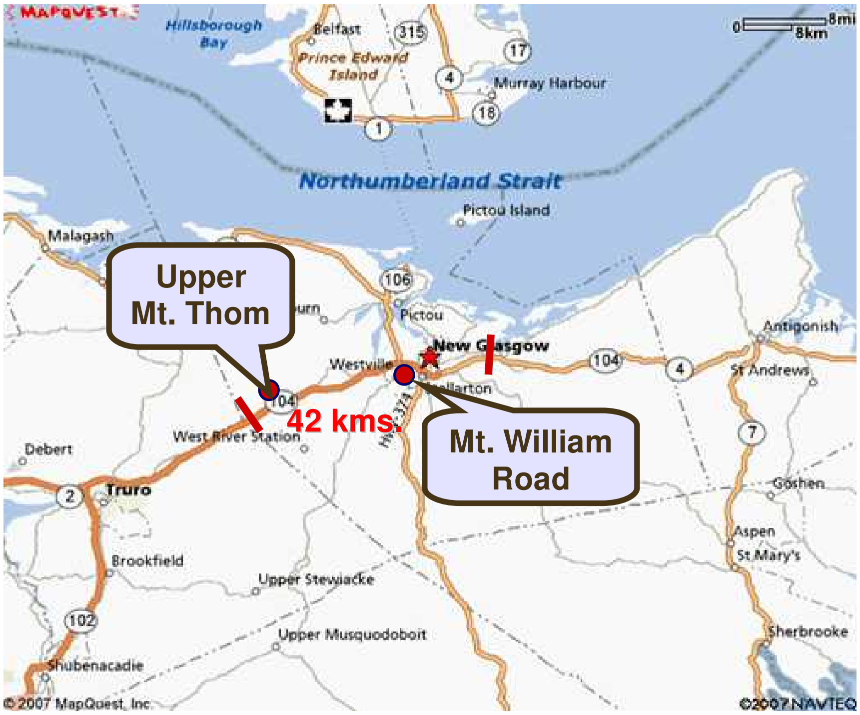

Figure 1 - Demonstration Area in Nova Scotia.

The RoadWatch IR sensor is able to sense a 1º C temperature change in 1/10 of a second (accuracy of ± 1 º C and a response time of 100 milli-seconds). The AVL unit was able to provide position fixes at 2 second intervals. Shao and Lister [3] recommend a sampling interval of 4 to 5 meters. For this reason, the speed of the patrol vehicle was slowed to 35 kilometers per hour (9.7 meters/second). This provides data points with temperatures (air and pavement), location and time at intervals of 20 meters or about 2100 data points per run along the test route. For highway applications this proved sufficient.

Thermal fingerprints are generally produced for three set weather types: Extreme, Intermediate, and Damped [4]. Extreme in this case means clear and calm conditions which yield the greatest temperature variations along the road surface. Intermediate is defined as partly cloudy conditions with light to moderate winds. Damped refers to the weather conditions that will yield the least temperature variation along the roadway; overcast and windy conditions.

3. MODERN THERMAL FINGERPRINTS

AMEC meteorologists coordinated the IR runs with NS TIR staff. IR run data from the previous night was extracted daily and analysed against the actual weather along the route at the time of the run. A total of 23 runs were performed over the period 6 February to 13 March 2007. The analysis consisted of the following steps:

1. Confirmation of suitability and classification according to weather type;
2. Fixing the run start and end points;
3. Scanning the run data to remove any erroneous readings;

4. Calculation of the mean road surface temperature for the entire run and then the deviations from that mean for each data point;
5. Refining positional alignment of run data points;
6. Generating and filtering the thermal profile; and
7. Averaging multiple runs for each of the set weather types to yield a final thermal fingerprint (one for each of E, I, and D).

The next exercise was to confirm that the classic thermal fingerprint reported in the literature [5] could be produced. This was quickly accomplished. The classic two-dimensional representation of thermal fingerprints predates the development of Geographic Information Systems (GIS) applications. Figure 2 provides a modern representation of an Extreme thermal fingerprint for TCH 104 in Nova Scotia in a GIS map format. The diagram is composed of three parts. The upper panel presents land cover, over a broad area around the route and road temperature variations along the western half of the route and a lower panel provides these for the eastern half of the route. The insert, middle right panel in Figure 2, provides an aerial view of the topography over a broad area along the route together with the temperature variations from the mean along the roadway. This is important since the road's thermal behaviour is a function of the lay of the land spatially in three dimensions rather than just the elevation along the road itself.

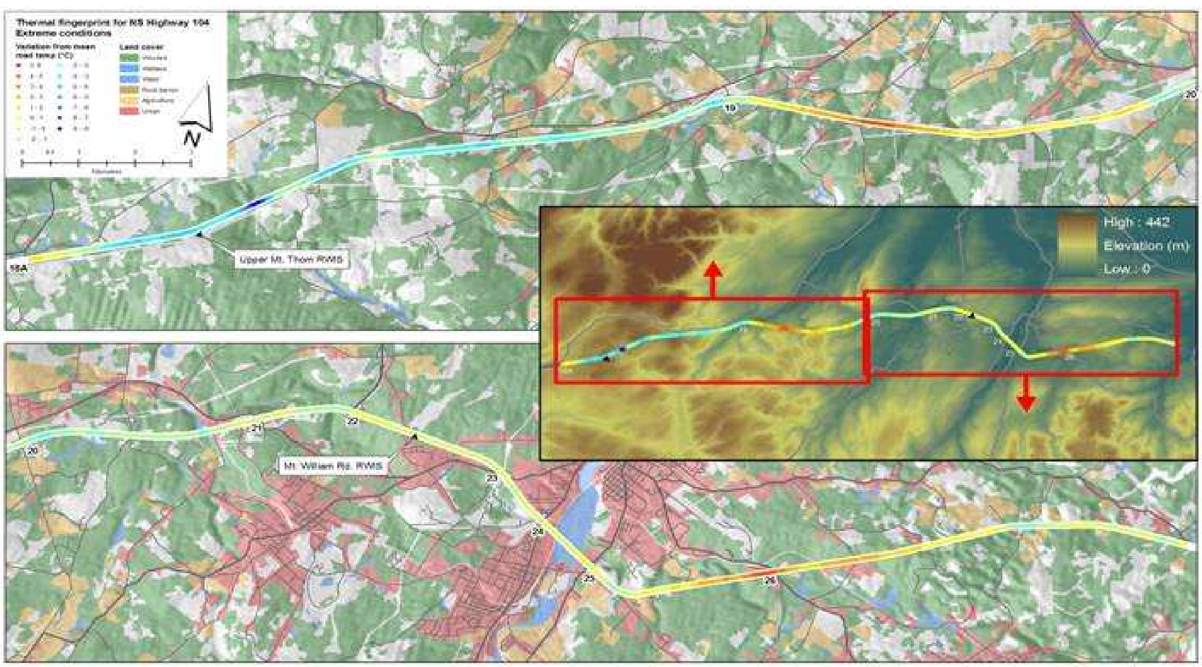

Figure 2 - Modern Extreme Thermal Fingerprint for TCH 104 in GIS format.

The legend in the upper left corner provides the colour codes for the land-cover and the temperature ranges corresponding to the colours of the road itself. The terrain map colours range from aqua for near sea level to dark brown at 442 meters above sea level. Finally, the precise location of the two RWIS is provided in all three panels.

This modern GIS thermal fingerprint representation provides a broad three-dimensional aerial view surrounding the road and its adjacent areas. The GIS database provided by NS TIR offers nearly 100 different user-selectable land cover categories. Other land cover data can be displayed for analysis and the entire representation can be easily rearranged. The thermal fingerprint data for the road itself was delivered to NS TIR in a GIS standard file format so that it could be easily imported into other GIS applications as well.

4. OPERATIONAL NIGHT ICING POTENTIAL SERVICE

The modern thermal fingerprint presented in Figure 2 is a powerful tool that imparts an enormous amount of information about the road's thermal behaviour. As such it possesses intrinsic value for winter road maintainers newly assigned to that section of roadway. It allows individuals to acquire, through some minutes of study, the intimate knowledge of the roadway's thermal behaviour that would otherwise have taken years of working the road to acquire.

A simple decision aid tool is needed to help road supervisors apply these complex thermal fingerprints operationally day to day. One application would be to determine when and where frost might form along a roadway on a given night. The RWIS forecast temperatures together with the thermal fingerprint corresponding to the expected prevailing overnight weather conditions can be used to generate useful guidance on this. The following preparatory steps are required:

1. Associate roadway portions with one of the two RWIS sites;
2. Segment the roadway – break it up into short discrete lengths;
3. Assign an offset from the mean temperature value to each segment for each of the three cases (E, I, and D); and
4. Determine the temperature differential between each roadway segment and its associated RWIS site.

Figure 3 illustrates the first step: association. A relationship needs to be established between each road segment and a neighbouring RWIS station. There are two RWIS stations along this 42 kilometre stretch of TCH 104. Figure 3 provides all three thermal fingerprints and the elevation profile. Note that all three fingerprint curves converge at a point approximately one third of the way from the western end of the route. This also corresponds roughly to the base of Mt. Thom and provides a suitable break point for the association exercise. Consider also that the weather at the Mt. Thom RWIS site would be very representative of the weather conditions over the western third of the route where elevations are higher. The western third of the route was therefore associated with the Mt. Thom RWIS site. The eastern two thirds of the route were associated with the Mt. William RWIS site whose weather conditions would be more representative of prevailing conditions from the base of Mt. Thom eastward to New Glasgow.

Next, each portion of the route needed to be divided into a number of much smaller segments. This is to capture the great road surface temperature variability along the route especially evident in the E and I fingerprints. Several attempts were made to devise segments of variable length according to the variation of temperature along the roadway or even land cover and elevation features. This proved to be extremely difficult. To facilitate automation, equal length segments were used with lengths of 2 kilometres, 1 kilometre, and 250 metres tested in turn. Segments of 1 kilometre length provided an optimal resolution for a highway application. Shorter segments may work well in an urban setting.

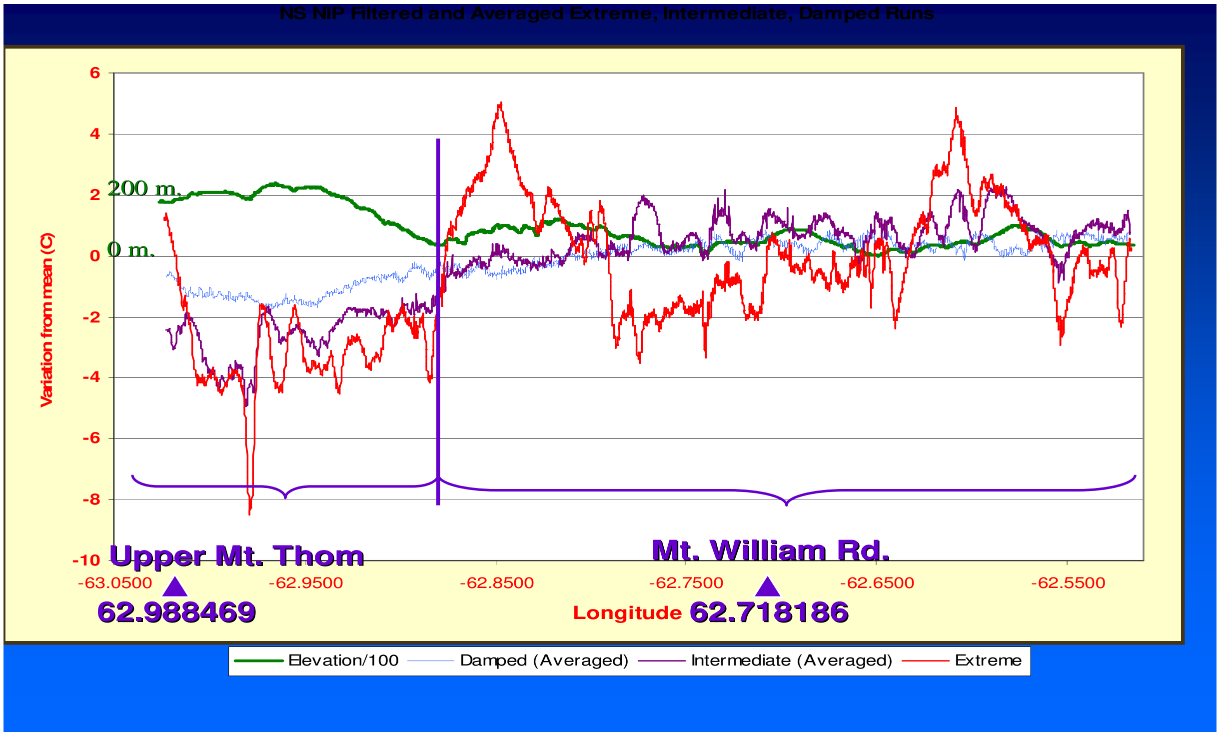

Figure 3 - Association of Road Portions with RWIS Sites.

The final step was to determine the temperature differential (offset) from the associated RWIS site for each of the kilometre long segments, and for each of the three weather types. In order to err on the side of caution, the coldest departure from the route mean temperature was selected for each segment and for each weather type.

Moving now to the frost forecast problem. The requirements for the formation of frost along any segment are:

$$\mathbf{T_r \leq 0\ ºC} \quad \text{and}$$

$$\mathbf{T_r \leq T_d}$$

Where T_r is the temperature of the road surface and T_d is the air dew point temperature. The steps in the determination of Night Icing Potential (NIP) are as follows:

1. Prepare atmospheric forecasts including wind, cloud cover and dew point for each RWIS site;
2. Run a thermodynamic heat-balance (or other) model to produce a point pavement temperature forecast for each RWIS site;
3. Type class the weather over the route for the coming night as Extreme, Intermediate, Damped, or Unsuitable (eg. precipitation expected);
4. Select the corresponding segmented thermal fingerprint for the route;
5. Calculate the forecast T_r for each segment for each hour through the night;
6. Determine if the forecast T_r for any segment will meet the above two conditions simultaneously;
7. Note the earliest time at which these two conditions are met; and
8. Prepare a GIS map with these times plotted for each segment.

5. NIP CASE STUDY

The process described above is best illustrated by reviewing an actual case. Figure 4 provides the RWIS forecast for Mt. Thom for the night of 12-13 March 2007. The clear weather of the afternoon which had yielded near 15 ºC pavement temperatures was forecast to remain clear overnight with very light winds over central Nova Scotia. The weather type class for the coming night was thus Extreme. Note that the dew point temperatures were forecast to rise over 10 ºC during the night. With clear skies and near-calm winds, the pavement surface temperatures were forecast to plummet, falling to below zero by 20:00, then to below the air temperature before midnight. At Mt. Thom itself, pavement temperatures were forecast to fall below the air dew point by 03:00 on the morning of 13 March; the earliest time for frost formation at the Mt. Thom RWIS site.

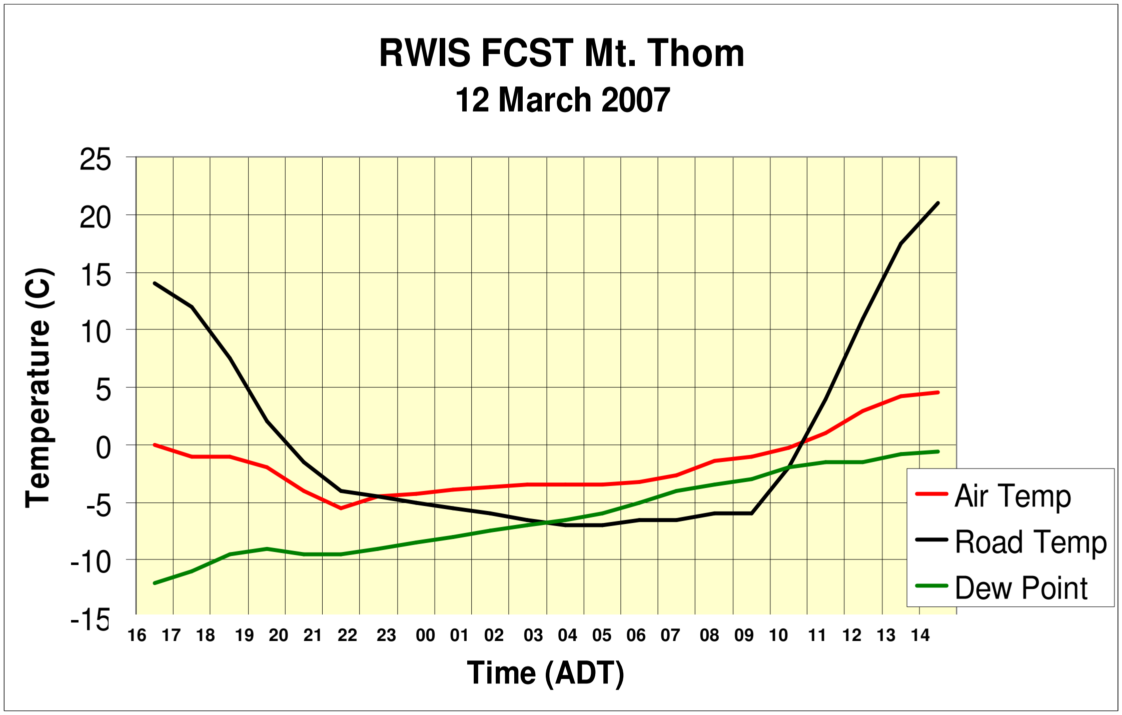

Figure 4 - RWIS Forecast for Mt. Thom for the Night of 12-13 March.

The NIP product is designed to determine if there is a potential for frost, a Night Icing Potential, for any segments of the stretch of roadway around an associated RWIS site, and if so, where and then return the earliest time when this could occur. The left-most 4 columns of Table 1 provide the same forecast temperature information (with all temperatures rounded to the nearest 0.5 degrees Celsius for simplicity) for the night of 12-13 March for Mt. Thom as are represented in Figure 4. The difference between the forecast road surface temperature and the dew point values, the 'Diff' column in Table 1, becomes negative at 03:00 on 13 March. When forecast pavement temperatures are below 0º C and below the air dew point; then there is a Night Icing Potential. These conditions are met at 03:00 and remain conducive for frost up to 09:30 on 13 March.

Table 1 - NIP Forecast for Mt. Thom and Adjacent Road Segments, 12-13 March.

	ADT	FORECAST			FCST	Segment Road Temp Difference					
DATE	TIME	Troad	Tdew	Diff		+3	+2	+1	-1	-2	-3
12	21	-4	-9.5	5.5		8.5	7.5	6.5	4.5	3.5	2.5
12	22	-4.5	-9	4.5		7.5	6.5	5.5	3.5	2.5	1.5
12	23	-5	-8.5	3.5		6.5	5.5	4.5	2.5	1.5	0.5
12	00	-5.5	-8	2.5		5.5	4.5	3.5	1.5	0.5	-0.5
13	01	-6	-7.5	1.5		4.5	3.5	2.5	0.5	-0.5	-1.5
13	02	-6.5	-7	0.5		3.5	2.5	1.5	-0.5	-1.5	-2.5
13	03	-7	-6.5	-0.5	NIP	2.5	1.5	0.5	-1.5	-2.5	-3.5
13	04	-7	-6	-1	NIP	2	1	0	-2	-3	-4
13	05	-6.5	-5	-1.5	NIP	1.5	0.5	-0.5	-2.5	-3.5	-4.5
13	06	-6.5	-4	-2.5	NIP	0.5	-0.5	-1.5	-3.5	-4.5	-5.5
13	07	-6	-3.5	-2.5	NIP	0.5	-0.5	-1.5	-3.5	-4.5	-5.5
13	08	-6	-3	-3	NIP	0	-1	-2	-4	-5	-6
13	09	-2	-2	0	NIP	3	2	1	-1	-2	-3
13	10	4	-1.5	5.5		8.5	7.5	6.5	4.5	3.5	2.5

From the corresponding Extreme thermal fingerprint, it is clear that other road segments along the western end of TCH 104 can be several degrees warmer and others colder than the forecast pavement temperatures at the Mt. Thom site itself. For road segments that are 3º C warmer than Mt. Thom, we can simply add +3 to the T_r - T_d values in the Diff column. Conditions for NIP are just barely met then at 08:00, 13 March (0 in Table 1). The same process can be repeated for road segments that are +2, +1, -1, -2, -3 º C different from the Mt. Thom site. Note that the calculation is performed using the forecast dew point temperature for the air mass for each successive hour in the night. Note also that the table provides local times.

For road segments that are much colder than Mt. Thom, the onset of frost will be correspondingly much earlier than at Mt. Thom itself because those road segments become colder than the forecast air dew point much earlier in the night. For warmer road segments, the onset of frost will be later than at Mt. Thom. Thus temperature differentials along the route can be converted into correspondingly earlier or later frost onset times for those segments. Proceeding in this way, the earliest possible time for the onset of frost, the time of interest to road maintainers, can be determined for each kilometre long road segment. Once these times are determined, they can be plotted for each road segment onto a GIS map. The resulting NIP chart for the west end of TCH 04 in Pictou County for the 'Extreme' night of 12-13 March 2007 is provided in Figure 5.

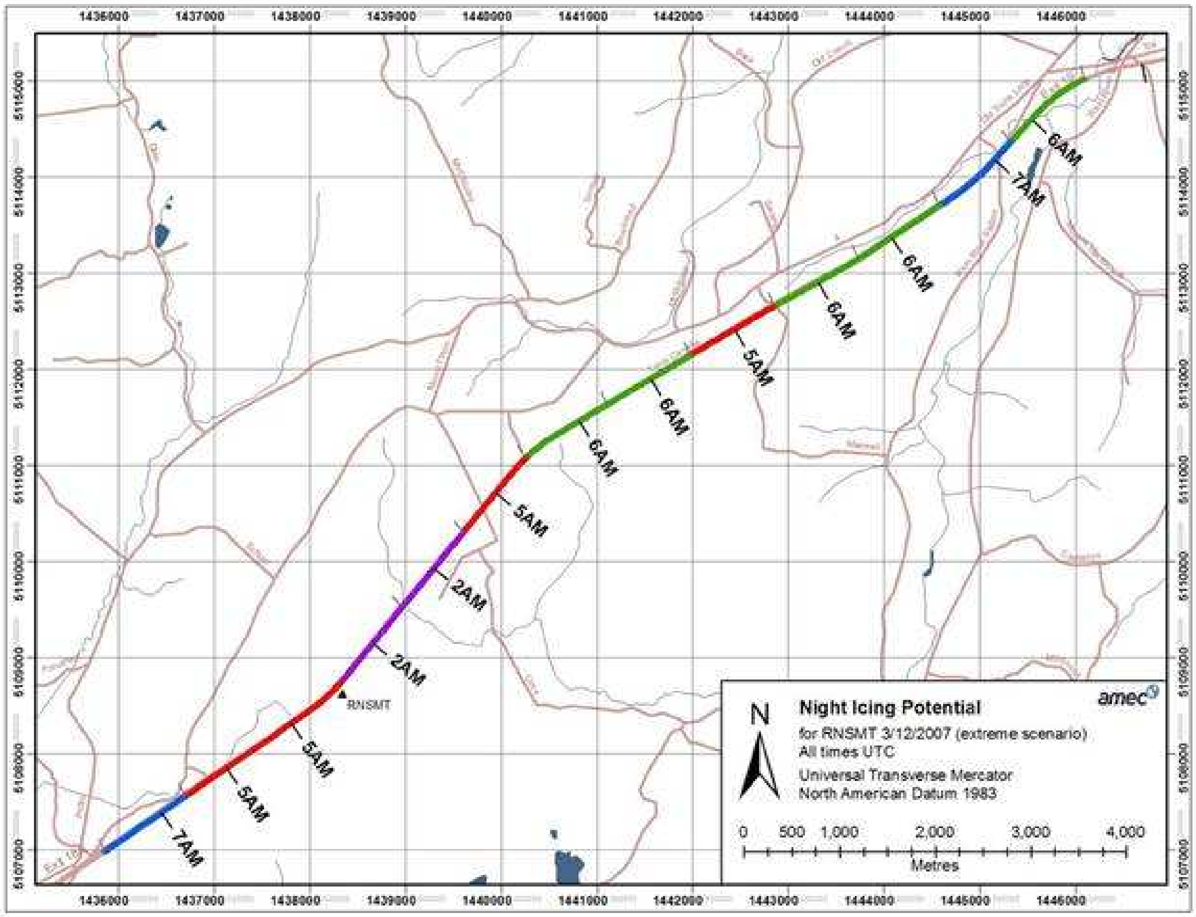

Figure 5 - Night Icing Potential (NIP) Output Chart for TCH 104 West for the Night of 12-13 March 2007.

6. OPERATIONAL EVALUATION

The NIP service was tested operationally in its' first year during the late spring of 2007 for several weeks and again for nearly 2 months in the fall of 2007. The tests consisted of the preparation of RWIS forecasts for the two RWIS sites and the preparation of the NIP output charts for those nights with a potential for icing over one or more road segments. NS TIR arranged road patrols, sometimes multiple patrols, to determine if signs of frost could be detected in any segments along TCH 104 in Pictou County. This was necessary since NIP involves forecasting frost anywhere along the entire length of the roadway and not just at the RWIS sites themselves. A total of 22 NIP forecasts in all (one per day and working only Monday to Friday) were generated and closely evaluated.

One of the simplest and best ways to test a system's ability to forecast a discrete event is with a two-by-two contingency table [6]. This tests the first part of the NIP generalized output; that icing is or is not expected to occur somewhere along the route. With an operationally significant event or outcome chosen, that of frost formation, this scheme is also one of the better approaches to assess the utility of a forecast. The generalized two-by-two contingency table is presented in Table 2.

Table 2 – Generalized Two-by-two Contingency Table

		FORECAST	
		Icing	No Icing
OBSERVED	Icing	✔ - A	✗ - B
	No Icing	✗ - C	✔ - D

Over the two verification periods, using very strict definitions for frost formation, the following results were recorded:

A = 5 B = 0
C = 6 D = 11
Total events for verification = 22

From the simple two-by-two contingency table some useful statistics can be calculated. The Percent Correct (PC) metric gives the ratio of the total number of events that were correctly forecast (A+D) to the total number of forecasts. The PC score achieved, 72.7%, is encouraging given that the verification is evaluating a detailed end product generated with some assumptions against the observation of icing along an entire route and tests a new product without any adjustments. A PC score in this range is quite good.

Two other very useful statistics in judging the quality of a forecast are the correct Yes events and the correct No events [7]. The relationships and results are as follows:

$$\text{YES Forecasts} = A / (A + C) = 5 / (5 + 6) = 5 / 11 = 45.4\ \%$$

$$\text{NO Forecasts} = D / (B + D) = 11 / (0 + 11) = 11 / 11 = 100\%$$

The Yes Forecast score is quite low but these errors are less serious and the verification scheme applied was demanding. Several forecasts expected icing over just one or two road segments just before dawn when none was actually found. These were counted as incorrect Yes forecasts. Plus, NIP is designed to err on the side of safety so it should, and it does, over-forecast icing events. The No Forecast score is 100% which shows that NIP did not commit any of the more serious errors: forecasting no icing when icing actually occurred. This is a particularly good outcome as it confirms that the guidance can be used with very high confidence when it indicates no icing anywhere along the route.

7. STRENGTHS AND LIMITATIONS

The new NIP product has been well received by the target user community – winter road maintainers. It is a valuable aid for winter road maintenance supervisors dealing with potential frost events. Based on the forecast for the RWIS site, the atmospheric forecast, and the appropriate thermal fingerprint for the prevailing forecast weather type, NIP provides a user-friendly guide as to where frost may form, if any, and the earliest time for the onset of frost for each road segment so affected. Prepared in late afternoon for the coming night, it provides an excellent planning tool for the winter maintainer who can then schedule road patrols for the various segments at about, or shortly after, the earliest frost onset time. Perhaps the best indicator of value is the fact that over the last 2 years since the original 42 km demonstration project, NS TIR has applied its IR mapping approaches and extended NIP services to an additional 390 kilometres of highways throughout Nova Scotia. Other major provincial road jurisdictions in Canada are also considering NIP applications.

It has been shown by Shao et al [8], that once the thermal maps have been prepared, they can be used with confidence for many years. So the IR data collection only needs to be done once along with the classification of the runs into the three weather types. This is because the physical features surrounding the roadway as well as the roadway itself, all factors which affect a road's thermal response, typically do not change markedly from year to year so the road's thermal characteristics only vary slightly over time.

In some jurisdictions, there may be little or no labour savings gained through the use of NIP products since this is dependant on contractual arrangements for the road patrol drivers. However, for most jurisdictions, NIP should lead to savings in fuel and wear and tear on the patrol vehicle as well as, ultimately, savings in salt expenditures. There would also be reduced exposure to liabilities. Indirect benefits would likely include enhanced safety for the motoring public as well as reduced greenhouse gas emissions (fewer patrols) and reduced salt loading in the environment.

It can be shown that using the cost-effective IR data collection and thermal map preparation approaches described herein, the NIP service can pay for itself quite easily within a few years based on salt savings alone. Clearly though, the savings are substantially more especially if some accidents with serious injuries can be avoided. The completion of detailed cost-benefit analyses is best left to individual maintenance organizations which are better able to define and quantify specific categories and amounts of savings for their particular circumstances since these can vary markedly from jurisdiction to jurisdiction.

NIP does have limitations and it is important to understand these. There has been no attempt to resolve the moisture variations along the roadway that may arise with certain wind directions or at different points in the winter season when adjacent water bodies may still be unfrozen. The moisture fluxes along the roadway can be quite large and often more complex than the thermal fluxes. The NIP product simply uses the forecast dew point temperatures for each hour in the night prepared for the associated RWIS site(s) and applies those evenly for the entire route. Using the forecast dew points for each hour in the night does help as does the association of road portions with RWIS sites that are 'representative' of the weather in the micro-climatic area. So as the RWIS station density increases and the associations are refined, better moisture flux resolution and weather representativeness will lead to improved NIP product performance.

This shortcoming, not resolving the moisture fluxes, is what motivated the selection of the name for the product and service: Night Icing Potential. NIP does not profess to be an absolute categorical forecast of frost formation. What it tries to determine is, first, whether frost could form anywhere along the route at night and, if so, where together with an estimate of the earliest time it could form.

8. CONCLUSIONS

This project demonstrated an efficient cost-effective approach for the preparation of road thermal fingerprints. It also advanced the state-of-the-art in the presentation of road thermal fingerprints through the use of modern GIS mapping techniques. Conversion to GIS standards should also facilitate the use of road thermal profiles in other areas.

This project devised a new operational service, the Night Icing Potential (NIP) service, for use in cold climates to determine if, where, and when frost may form. NIP provides a simple early warning and planning tool for road maintenance supervisors to use on 'non-weather' nights (nights when no precipitation is forecast) which make up the majority of nights through the fall, winter and spring seasons.

Preliminary verification work shows that NIP was correct nearly three quarters of the time. NIP showed particular strength in not missing any icing events and so avoiding the most serious and potentially dangerous kinds of errors. NIP has performed well at what it claims to be: a guide to whether icing is expected anywhere along an entire route and, if so, then providing the earliest time for the onset of the frost formation process for each kilometre-long segment of the roadway.

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[1] Gustavsson, T. & Bogren J. (1988). Thermal Mapping by Use of Infrared Technique. Proceedings of the 4th International Conference on Weather and Road Safety, Florence, Italy.

[2] VTI. Vintermodellen, A Swedish Winter Maintenance Management System. Prepared in part for COST Action 353.

[3] Shao, J. & Lister P.J. (1995). Data Filtering for Thermal Mapping of Road Surface Temperatures. Meteorological Applications, Vol. 2, pp. 131-135.

[4] Thornes, J. E.. Thermal Mapping and Road-Weather Information Systems for Highway Engineers. Highway Meteorology, ed. By A.H. Perry and L.J. Symons, E&FN Spon, London, pp. 39-67.

[5] Shao J., Swanson J.C., Patterson R., Lister P.J., and McDonald A.N. (1997). Variation of Winter Road Surface Temperature Due to Topography and Application of Thermal Mapping. Meteorological Applications, Vol. 4, pp. 131-137.

[6] Thornes J.E. & Stephenson D.B. (2001). How to Judge the Quality and Value of Weather Forecast Products. Meteorological Applications, Volume 8, pp. 307-314.

[7] Olson R.H. (1965). On the Use of Bayes' Theorum in Estimating False Alarm Rates. US Weather Bureau, Boulder, Colorado, USA.

[8] Shao, J. & Lister P.J., Hart G.D., & Pearson H.B.. Thermal Mapping: Reliability and Repeatability. Vaisala TMI Ltd, Vaisala House, Bristol Road, Birmingham, UK.