NIGHT ICING POTENTIAL

DEMONSTRATION PROJECT

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ABSTRACT

This paper presents a very cost-effective approach for the preparation of thermal fingerprints and the forecasting of potential night icing situations. A Nova Scotia Transportation and Public Works (NS TPW) patrol vehicle equipped with an infra-red (IR) sensor and an Automatic Vehicle Location (AVL) service was used to perform IR data runs along a section of highway 104 in Pictou County, Nova Scotia. The signal from the IR sensor was fed directly into the AVL unit which relayed the positional, timing, and temperature information directly to the AVL provider, Grey Island.

AMEC meteorologists coordinated the IR runs with NS TPW staff and extracted the Grey Island AVL data daily for analysis against the weather from the previous night. The data were mathematically filtered, aligned, and averaged. Thermal fingerprints for three weather types (Extreme, Intermediate, and Damped) were produced in a GIS format.

The thermal fingerprints for highway 104 were then associated with the two Road Weather Information Systems (RWIS) along the route. The route was divided into equal segments and the coldest temperature deviation from the mean along each segment was assigned to the entire segment. Forecasts of pavement temperature and air dew point were used with the fingerprint corresponding to the coming nights prevailing forecast weather to determine the earliest time at which frost could form for each road segment. The resulting GIS map with colour coded road segments and time stamps of the potential onset of icing provides an effective new road maintenance operations planning tool.

A GIS-based format for thermal fingerprints and forecast presentation will be presented. The logic and steps in the production of this innovative Night Icing Potential (NIP) chart product will be presented and its limitations described.

INTRODUCTION

Thermal imaging of roadways using infra-red (IR) sensors was first developed about two decades ago. IR sensing has been used to quantitatively describe the thermal behaviour of a roadway at night under various weather conditions along its entire length (1). The diagrams produced are generally referred to as thermal fingerprints. As more roads in an area are 'fingerprinted', a two-dimensional thermal map for an entire road network, or part of it, can be produced.

Road Weather Information Systems (RWIS) monitor atmospheric and pavement conditions at a single point and forecasts of future road surface temperature and condition provide a solution only at the RWIS locations. Thermal fingerprints provide a means of determining which road segments are colder or warmer than its 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 mild and very moist winter climates such as are found in the southern United Kingdom where the formation of frost on roadways is a dominant winter road maintenance problem. Using RWIS data and forecasts together with thermal fingerprints provides a means of determining where along a roadway surface temperatures may drop to below 0º Celsius over the coming night. With early morning relative humidity values in excess of 97% on virtually all nights, one can then assume a high likelihood that frost will form on those sections of roadway where road surface temperatures dip 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 all along the full length of the roadway but frost may not be present at all or form only along some sections. This is because all of the necessary conditions for frost to form on the roadway have not been met. Specifically, road surface temperature must drop to below freezing and the road surface temperature must be below the air dew point. To forecast where and when frost will form, if at all, one must determine where and when road surface temperatures will meet these two conditions.

Producing thermal fingerprints and thermal maps in the traditional manner was prohibitively expensive in cold climates where the formation of frost on roadways is less prevalent and the benefits to be gained smaller. Further, the ultimate end use of these products had never been advanced to the point of providing a simple, operationally useful product to guide the maintenance decisions of road supervisors. Still the formation of black ice on roadways is a particularly insidious road hazard that is especially difficult to deal with. Though much less frequent in Canada, this treacherous phenomenon needs to be addressed. Modern informatics tools can be effectively applied to determine precisely when and where there is a night icing potential. This paper provides some new approaches.

COST-EFFECTIVE THERMAL FINGERPRINTS

This demonstration project used a very cost-effective approach for the preparation of thermal fingerprints. Officials of the Nova Scotia Transportation and Public Works (NS TPW)

department acquired all of the IR data themselves. A patrol vehicle was already suitably equipped with a Sprague RoadWatch IR sensor and an Automatic Vehicle Location (AVL) unit. The AVL service provided by Grey Island Systems Inc. collects vehicle location and time information using the Global Position System (GPS) and provides this information back to NS TPW through the Internet. The IR sensor was interfaced directly into the AVL unit so that road surface and air temperatures from the RoadWatch unit were also relayed to Grey Island along with the location and time information. In this way, NS TPW assumed, as part of their regular road patrolling, the data acquisition portion of the thermal fingerprint production process.

A section of highway 104 in Pictou County, Nova Scotia, was selected for this demonstration project (Figure 1). The test length commenced just east of New Glasgow and ran 42 kilometers along the 104 to the Pictou County line halfway to Truro. There are two RWIS sites along the route: Upper Mount Thom and Mount William Road. The terrain varies significantly along the route, with Mount Thom known to be particularly prone to dangerous driving conditions due to local weather and elevation effects.

FIGURE 1 Demonstration area

All of the runs were performed starting from the west end of the route and driving in the East-Bound (EB) lane. The Sprague RoadWatch IR sensor claims to be able to sense a 1° C

surface temperature change in 1/10 of a second (accuracy of ± 1 ° C and a response time of 0.1 seconds). The Grey Island AVL unit was able to provide regular position, and therefore temperature and time fixes, at 2 second intervals. Shao and Lister (2) 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 a set of temperature and locations readings at intervals of 20 meters or about 2100 data points per run along the test route.

Thermal fingerprints are generally produced for three set weather types: Extreme, Intermediate, and Damped (3). Extreme in this case means clear and calm conditions which yield the most extreme 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.

MODERN THERMAL FINGERPRINTS

AMEC meteorologists coordinated the IR runs with NS TPW staff. IR run data was extracted daily and analysed against the weather from the previous night along the route. 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. Calculation of mean road surface temperature for the entire run and deviations from the mean for each data point;
4. IR data filtering of the road surface temperature deviations from the mean;
5. Positional alignment of run data; and
6. Averaging multiple runs under the same weather condition classification.

Runs were classified as Extreme, Intermediate, Damped, or Unusable. Whenever there had been any precipitation of any type, the roads had been treated, or there were weather fronts moving through the area, the run was deemed unusable and discarded.

Occasionally, the IR sensor was not able to acquire a reading and errors, coded as 999, appeared in the road surface temperature data. These needed to be removed. Since runs were not all started at exactly the same point and the speed varied during each run, careful alignment of the data sets from successive runs was required. The eastern-most start point from the west end of the route over all of the runs was chosen as the common start point and all data west of this point were discarded. Similarly, the western-most end point at the east end of the route was established as the common end point for all runs.

The average road surface temperature for the entire run was then calculated. For each data point, the mean road surface temperature for the run was subtracted from the actual road surface temperature. This gave the deviation from the mean along the run and identified those road segments that were warmer and colder than the mean.

The road environment was quite dirty, with many surface irregularities and slight variations in vehicle speed causing the IR data to be noisy. Cleaning the data consisted of

removing spurious outlying data points. A non-recursive low-pass adjustable filter described in Shao and Lister (2) was used for this purpose.

Latitudes and longitudes provided with the AVL service were used to calculate the actual position along the route from the start point. In this way, the curves generated from successive runs could be lined up correctly for comparison and averaging. Finally, output curves from the collection of runs according to each weather type were averaged to arrive at a single filtered and averaged IR fingerprint for each weather type: Extreme, Intermediate, and Damped.

The next exercise was to confirm that the classic thermal fingerprint reported in the literature (4) could be produced. Figure 2 shows the thermal fingerprint for the Extreme case for Highway 104. Two graphics are aligned vertically in the figure: the abscissa of the top graph is distance in kilometres along the roadway while that of the bottom graph is longtitude along the roadway.   These are correctly aligned. The ordinate of the bottom section of the diagram provides elevation of the roadway, in meters, above mean sea level, while the ordinate of the upper section provides the deviation of the road surface temperature from the mean in degrees Celsius.

The shapes that appear in the lower part of the diagram are rudimentary indicators of physical features along Highway 104. Rectangles represent built-up areas while green triangles represent vegetation and, when stacked vertically, treed areas. Parallel lines denote overpasses or bridges.
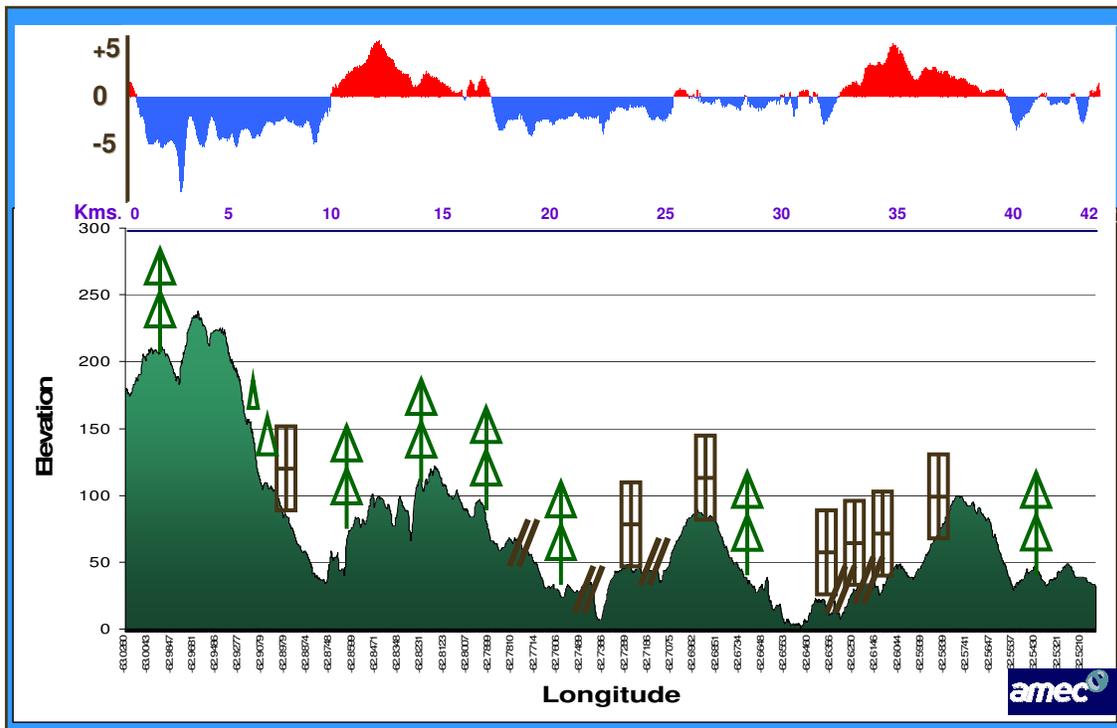

FIGURE 2 Classic Extreme Thermal Fingerprint for Highway 104 in Nova Scotia

The classic representation of thermal fingerprints predates the development of Geographic Information Systems (GIS) applications which offer significant advantages for the representation of thermal fingerprints. Figure 3 is a modern representation of the same Extreme thermal fingerprint for Highway 104 in Nova Scotia in a GIS map application. The diagram is composed of an upper panel representing the western half of the route and a lower panel representing the eastern half of the route. Since land cover also influences road thermal behaviour, the legend in the upper left corner provides the color code for the land-cover. This is provided in the two panels as a two-dimensional aerial view surrounding the road and adjacent areas. The GIS database provided by NS TPW allowed selections from nearly 100 different land use categories for analysis, allowing the richer representation to be user definable.

The insert in the middle right provides an aerial two-dimensional view of the terrain features along the route. The terrain mapping colors range from aqua for sea level to dark brown for 442 meters above sea level. This is important since the road's thermal behaviour is more a function of the lay of the land spatially in two dimensions than just the instantaneous elevation along the road itself.
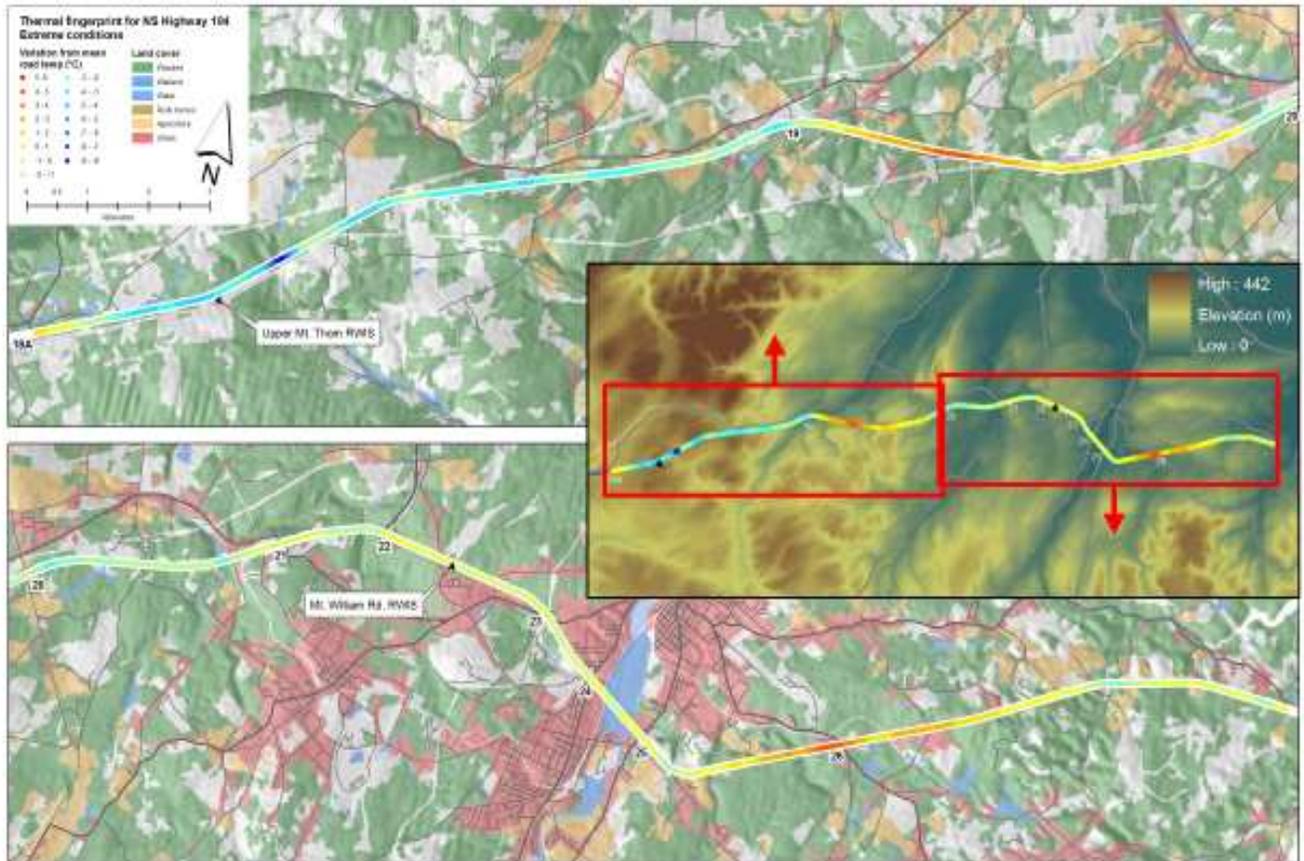

FIGURE 3 Modern Thermal Fingerprint (Extreme) for Highway 104 in Nova Scotia in GIS format

The legend in the upper left of Figure 3 also provides the color code for the temperature variations from the mean (not from 0º C) of all temperatures along the route for this Extreme case. The temperature variations along the roadway are represented in color on the road itself in the upper and lower panels of land cover and in the topographic insert in the middle right. The precise location of the two RWIS along this portion of highway 104, Upper Mt. Thom and Mt. William Road, are also provided.

This GIS representation for a thermal fingerprint provides much more information than the classic representation. Users can import and display other land cover data for analysis and can very easily modify the whole representation at will. Finally, the thermal fingerprint data itself can be imported into other GIS applications for other purposes. Thermal fingerprints for the three weather types were produced in this format and made available as a digital layer for other RWIS applications.

OPERATIONAL NIGHT ICING POTENTIAL SERVICE

The modern thermal fingerprint presented in Figure 3 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 Highway 104. It allows individuals to acquire, through fifteen minutes of study, the intimate knowledge of the roadway's thermal behaviour that would otherwise have taken many years of working the road. Despite this, the modern thermal fingerprint in this form remains a challenge to use operationally.

More work was required to develop a simple tool to determine which road segments on a given night might be subject to the formation of frost and, if there was a night icing potential, when would frost form and on which specific segments along the road. The following steps were required:

1. Associate portions of the roadway with one of the two RWIS sites;
2. Break the roadway up into discrete segments; and
3. Determine the temperature differential from the associated RWIS for each roadway segment.

Figure 4 illustrates the first step--association. A relationship was needed between different road segments and a neighbouring RWIS station, since forecasts prepared for the RWIS sites provide the starting point in assessment of Night Icing Potential (NIP). Since there are two RWIS stations along this 42 kilometer stretch of Highway 104, a coarse first guess association could have been done simply by dividing the route in half and assigning the west half to the Mt. Thom site and the eastern half to the Mt. William site.

Figure 4 provides all three thermal fingerprints: Extreme in red, Intermediate in purple, and Damped in blue, together with the elevation curve in green. All three 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 in the association exercise. 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 which happens to be approximately half-way along the eastern two-thirds of the route.

Next each portion of the route needed to be divided into a number of smaller segments. Several attempts were made to devise segments of differing lengths according to the variability of temperature along the roadway or other land cover and elevation features. To continue with such an approach would have been extremely difficult and time consuming. In the interest of efficiency and to facilitate automation, it was decided to proceed with segments of equal length. Equal segment lengths of 2 kilometers each, 1 kilometer each, and 250 meters each were tried. Segments of 1 kilometer length provided an optimal resolution for a highway application such as this. Although it was felt that 250 meter segments were too fine, they may work well in an urban setting.

The final step was to determine the temperature differential 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.
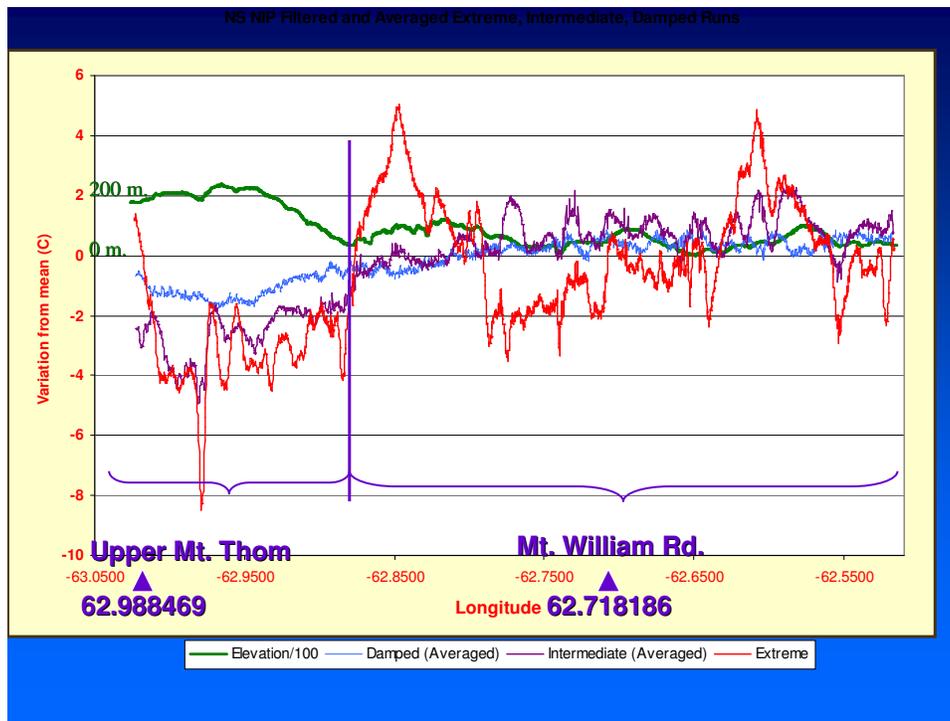

FIGURE 4 Association of road portions with RWIS sites

With the thermal fingerprint portions now associated with the appropriate RWIS site and the temperature differentials calculated for each road segment for each weather type (Extreme, Intermediate, and Damped), an operational NIP service that works in a cold climate is

possible. The requirements for the formation of frost, a night icing potential, 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 provision of a NIP service are as follows:

1. Prepare atmospheric forecasts including wind, cloud cover and dew point for each RWIS site;
2. Run a heat-balance model to produce a 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;
4. Select the corresponding segmented thermal fingerprint for the route;
5. Using the RWIS forecast and the appropriate fingerprint for the coming night, calculate the forecast road surface temperature for each segment for each hour through the night;
6. Determine if the forecast road surface temperature for any segment will dip below zero and below the forecast air dew point for that time of the night and note the time at which this would occur; and
7. Prepare a GIS map with these times for each segment.

NIP CASE STUDY

The process described above is best illustrated and understood by reviewing an actual case. Figure 5 provides the RWIS forecast for Mt. Thom for the night of 12-13 March 2007. The weather was forecast to be clear and calm over central Nova Scotia, giving it a NIP classification of Extreme. Note that the air dew point temperatures were forecast to rise nearly 10 degrees Celcius during the night. With skies clear after a clear day, the warm, nearly 15 ºC afternoon pavement surface temperature was forecast to plummet, falling below zero by 20:00, then to below the air temperature at 22:30. At Mt. Thom itself, pavement temperature would not fall to below the air dew point until just before 03:00 on the morning of 13 March. This is the earliest time at which frost would form at the Mt. Thom RWIS site. The goal was to determine if there was a potential for frost, a night icing potential, for any other segments of the stretch of Highway 104 in Pictou County, and if so, at what time?

Table 1 provides the same forecast road surface and dew point temperatures as are represented in Figure 5. The difference between these two values, the 'FORECAST - Diff' column, becomes negative at 03:00 on 13 March. With forecast pavement temperatures at that time below 0º C and below the air dew point, there was a Night Icing Potential at the RWIS site just before that time. Conditions remained conducive for NIP up to 10:00 on 13 March.
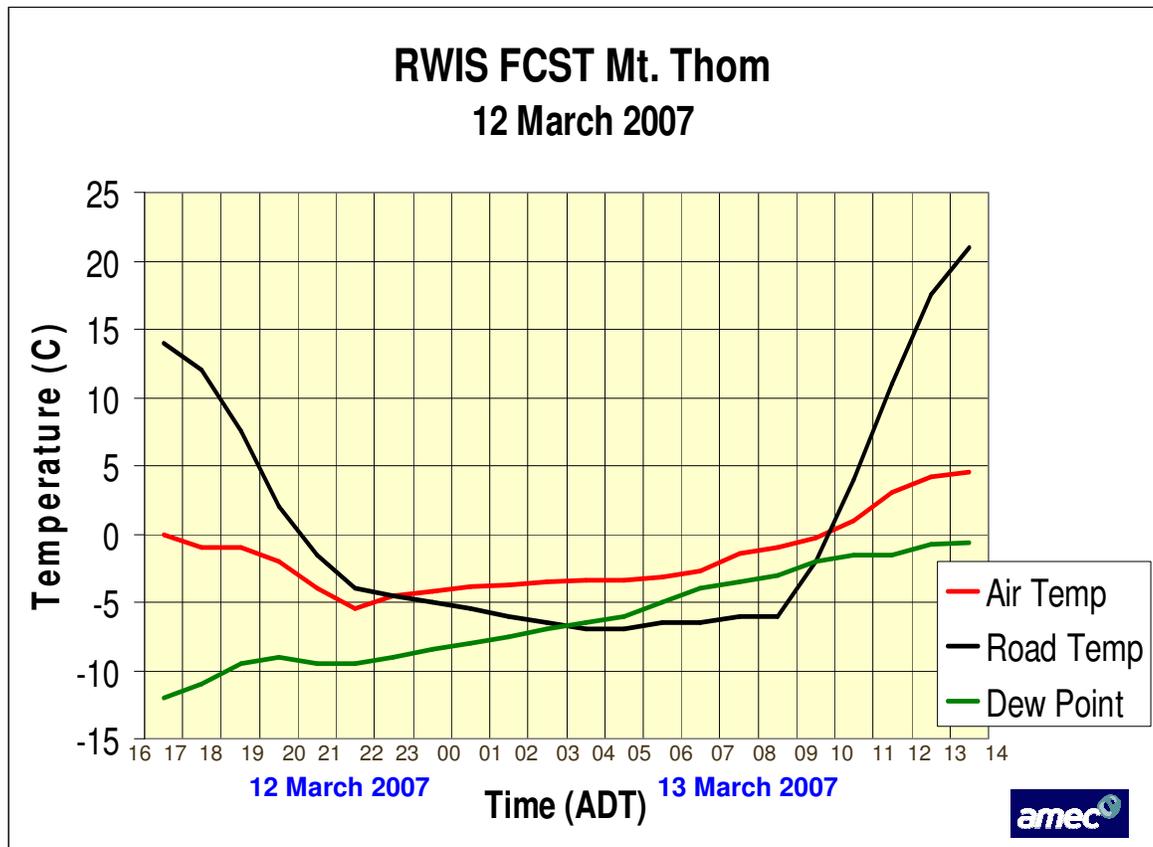
FIGURE 5 RWIS forecast for Mt. Thom for the night of 12-13 March 2007

	ADT	FORECAST					ROAD SEGMENTS					
DATE	TIME	Rd Temp	Dew Pt	Diff		+3	+2	+1	-1	-2	-3
12	9	-4	-9.5	5.5		8.5	7.5	6.5	4.5	3.5	2.5
12	10	-4.5	-9	4.5		7.5	6.5	5.5	3.5	2.5	1.5
12	11	-5	-8.5	3.5		6.5	5.5	4.5	2.5	1.5	0.5
12	12	-5.5	-8	2.5		5.5	4.5	3.5	1.5	0.5	-0.5
13	1	-6	-7.5	1.5		4.5	3.5	2.5	0.5	-0.5	-1.5
13	2	-6.5	-7	0.5		3.5	2.5	1.5	-0.5	-1.5	-2.5
13	3	-7	-6.5	-0.5	NIP	2.5	1.5	0.5	-1.5	-2.5	-3.5
13	4	-7	-6	-1	NIP	2	1	0	-2	-3	-4
13	5	-6.5	-5	-1.5	NIP	1.5	0.5	-0.5	-2.5	-3.5	-4.5
13	6	-6.5	-4	-2.5	NIP	0.5	-0.5	-1.5	-3.5	-4.5	-5.5
13	7	-6	-3.5	-2.5	NIP	0.5	-0.5	-1.5	-3.5	-4.5	-5.5
13	8	-6	-3	-3	NIP	0	-1	-2	-4	-5	-6
13	9	-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

TABLE 1 NIP forecast for Mt. Thom and adjacent road segments, 12-13 March 2007

Other road segments along Highway 104 in Pictou County can be several degrees warmer or colder than the forecast pavement temperatures at the Mt. Thom site itself (see the rightmost six columns in Table 1). 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 at 09:00, 13 March. The same process can be repeated for road segments that are +2, +1, -1, -2, -3 , etc. º C difference from the Mt. Thom site. Note that the calculation is performed using the forecast air dew point temperature for each successive hour in the night.

We see that for road segments that are much colder, the onset of frost will be much earlier than at Mt. Thom. For warmer road segments, the onset of frost will be later than at Mt. Thom. Proceeding in this way, the earliest possible time for the onset of frost can be determined for each kilometre long road segment. Once these times are determined, they can be plotted for each road segment in a GIS application. The resulting NIP chart for the west end of Highway 104 in Pictou County for the night of 12-13 March 2007 is provided in Figure 6.
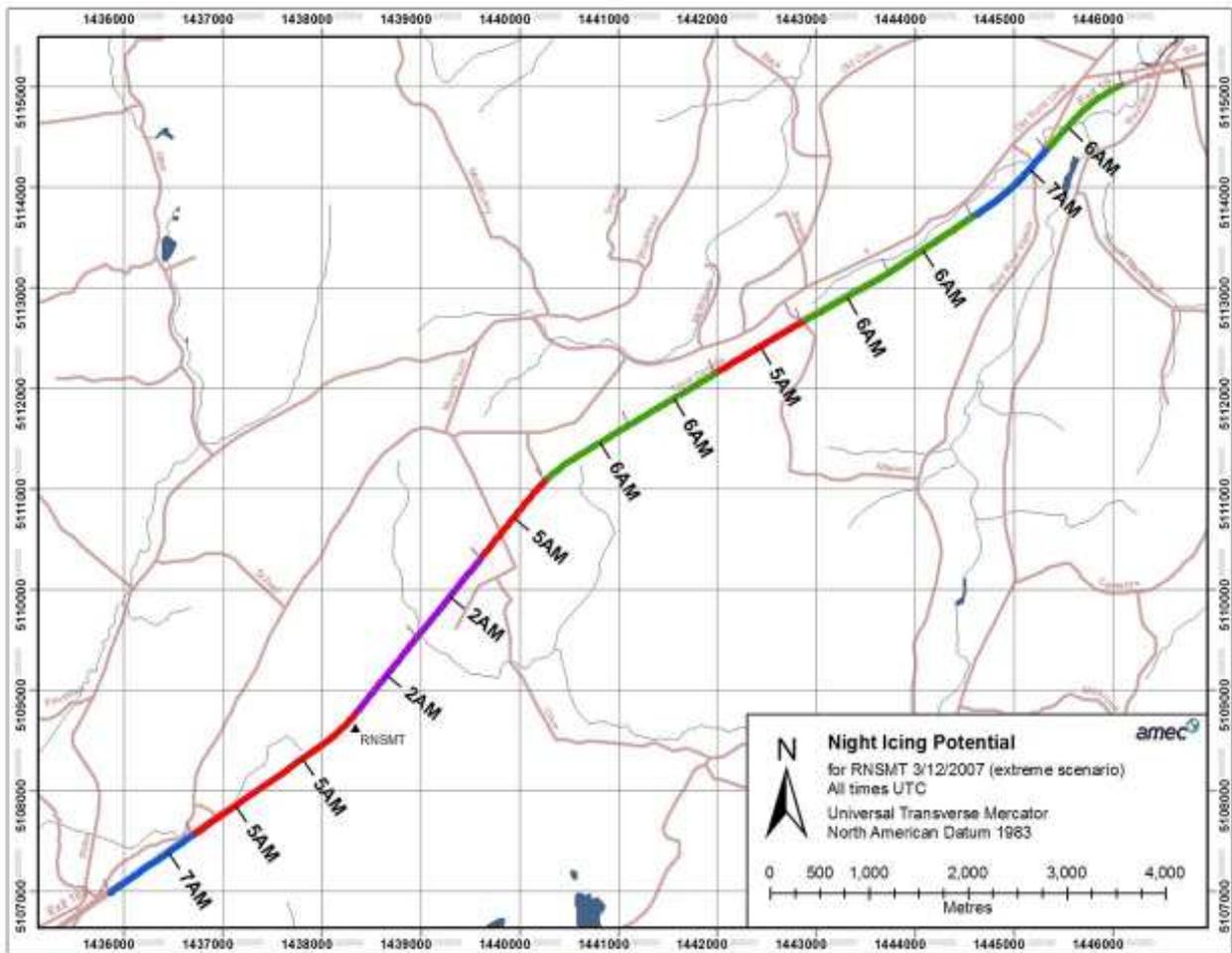

FIGURE 6 Night Icing Potential (NIP) chart for Mt. Thom for the night of 12-13 March 2007.

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 which are particularly difficult to deal with. 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 guide as to where frost may form, if any, and the earliest time for the onset of frost for each road segment. Prepared in the middle of the 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. The alternative would be to plan patrols for many more hours on many more nights or, worse, needlessly pre-treat roads on many more nights.

It has been shown, see Shao et al (5), 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 association with the three weather types. This is because the physical features surrounding the roadway typically do not change drastically from year to year so the road's thermal characteristics do not change. Once major new construction on the roadway or immediately adjacent to the roadway is completed or some seismic event occurs that disrupts the road's thermal properties, then the thermal maps would have to be redone over the affected segments.

In some jurisdictions, there would be no labour savings because of contractual arrangements. However there would still be savings in fuel and wear and tear on the patrol vehicle as well as savings in salt expenditures. There would also be reduced exposure to liabilities. Indirect benefits would 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 thermal map preparation approach described earlier, the NIP service can pay for itself quite easily based on salt savings alone. Clearly though, the savings are substantially more than just that. The completion of detailed cost-benefit analyses is best left to individual maintenance organizations who are better able to define and quantify their specific categories and amounts of savings.

NIP does have limitations. The thermal response of the roadway along its entire length is mapped and is used as a thermal fingerprint. However, 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. Even on clear calm nights, the moisture fluxes along a roadway can be quite large and more complex than even the thermal response.

The NIP product simply uses the forecast dew point temperatures for each hour in the night prepared for the RWIS sites and applies those evenly for the entire route. The fact that the forecast dew points for each hour in the night are used helps. As the RWIS density increases, the NIP product will become better and better as it adds greater moisture flux resolution.

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 if frost could form anywhere along the route and, if so, when and where along the route the potential for frost

formation exists. It has several features built in, selecting the coldest temperature for each kilometre-long segment of the road and applying it over the whole segment for example, so that NIP will provide the earliest time at which the potential for frost formation arises.

OPERATIONAL EVALUATION

The NIP service was tested operationally in 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, Mt. Thom and Mt. William, and the preparation of the NIP output charts for those nights with a potential for icing along one or more road segments. NS TPW arranged patrols on the nights with some frost expected to determine if signs of frost could be detected in the appropriate segments between the RWIS sites and beyond in Pictou County.

Preliminary analysis of the data confirms that the NIP product is good at determining if frost is possible in any of the road segments. For most occasions where frost was expected somewhere along the road, patrols confirmed frost formation, although not always in the forecasted segment. Patrols were also conducted on nights when frost was not forecast for any road segments but conditions were close to being met. None of those patrols detected any frost under these conditions. Evaluation of the data collected are ongoing at the time of this writing.

CONCLUSIONS

This project achieved the following:

- It demonstrated an efficient cost-effective approach for the preparation of road thermal fingerprints;
- It used GIS applications to advance the state-of-the-art in the presentation of road thermal fingerprints; and
- It devised an operational service, the Night Icing Potential (NIP) service, for use in cold snowy climates to determine through the use of RWIS forecasts, together with the thermal fingerprint for the prevailing weather type, which and when specific road segments would be susceptible to frost formation overnight.

Preliminary analysis of the test results from a limited trial period indicates that the NIP service is performing quite well. NIP has not missed any frost events, which would be the most serious error it could commit since roads would remain untreated and dangerous driving conditions possibly present. A closer analysis of the test period results is underway and will be reported on. Testing on a larger scale is recommended.

ACKNOWLEDGEMENT

[1] Gustavsson, T. & J. Bogren, Thermal Mapping by Use of Infrared Technique. *Proceedings of the 4th International Conference on Weather and Road Safety*, Florence, Italy, 8-10 November 1988.

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

[3] 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.

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

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