Small-scale road surface temperature and condition variations across a road profile.

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ABSTRACT

Since their implementation, Road Weather Information Systems (RWIS) have mostly relied on point measurements from outstations to initiate and verify daily forecasts. Initially, spatial extrapolation was achieved by thermal mapping, but this is gradually being replaced by route-based forecasting techniques. Both techniques are similar in the sense that they use a point measurement, often taken from an outstation, to provide a spatial forecast of road surface temperatures around the road network at varying resolutions. A substantial research effort has been undertaken to understand and model the complex environmental conditions and mechanisms responsible for the variation in road surface temperatures around the road network. In particular, the interaction of varying geographical parameters around the road network (e.g. altitude, landuse, road construction, topography, etc) have been used to develop local climatological models and next generation RWIS products. This paper begins by taking the approach to the next level and explains how the same techniques can be used to look at variations in road surface condition across the width of a road profile, instead of just lengthways along a road. Temperature and condition both vary significantly across the profile, which immediately raises questions about the validity of current surveying practices. Furthermore, as the highway engineer has a duty of care to protect the motorist, do these smaller scale variations and processes need to be taken into account in road weather models? The implications of this need clarification, but the paper concludes by presenting a case for not including traffic parameterisations in route-based forecasts.

Keywords: road surface temperature, road surface condition, route-based forecasts, traffic

1. INTRODUCTION

Winter maintenance engineers base their nightly decision making by consulting a Road Weather Information System (RWIS) which combines weather forecast data with road temperature and condition data. The first generation of RWIS currently in use relies on methods and tools developed in the 1980s. Early 'Ice Detection Systems' simply comprised of a number of outstations which detected when ice had formed upon the integral road sensor. This approach was limited for two reasons. Firstly, as the ice had already formed, it was too late to pre-salt the network. Secondly, the sensor only provided a 'spot' measurement of road surface condition (RSC) and road surface temperature (RST) at a single location. It was unknown how representative this location was in comparison to the remainder of the network. This lack of spatial information was the motivation behind the development of thermal mapping techniques [8]. Thermal mapping utilises an infrared thermometer to conduct a thermal survey from a moving platform. It was assumed that if this was done across the road network over a number of nights of varying atmospheric stability, the variations in RST and RSC could be interpolated between outstations.

Throughout the 1980s, these technologies matured into an 'Ice Prediction System' which via an energy balance model, enabled RST and RSC to be forecast for each outstation before being interpolated with a thermal map. This system quickly spread across the globe and has been considerably refined as computer processing power and communications have improved. However, as technology has moved on, many of the components of the existing system are looking dated and the whole system is now being superseded by route-based forecasting techniques e.g. XRWIS: the neXt generation RWIS [2,15]. Instead of relying on forecast interpolations made by thermal mapping, complete with its inherent limitations [4], XRWIS models RST by considering the influence of the local geography on the road surface [2]. The forecast is displayed in a GIS environment and disseminated direct to the highway engineer via the Internet (Fig. 1). In addition to RST and RSC forecasts, a key feature of XRWIS is an automated decision making algorithm where salting routes are colour coded depending on the required action (Fig. 1c). Enormous potential exists for savings to be made by using this route-based forecasting approach by leaving the warmer routes untreated.
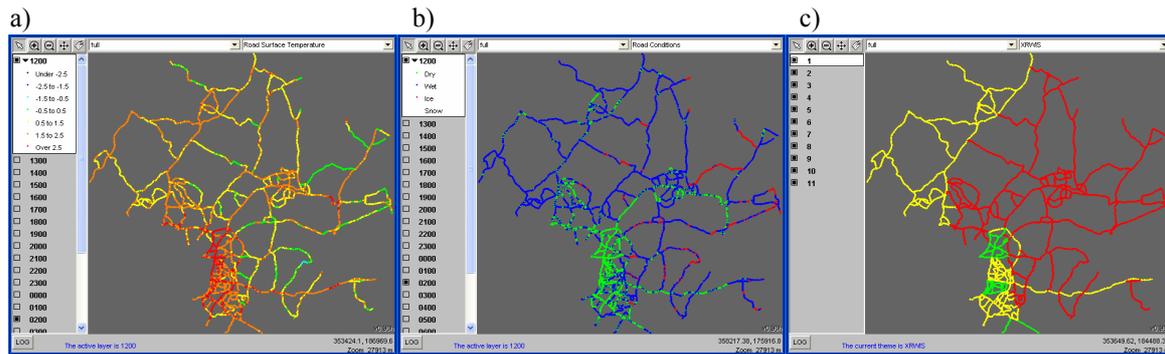
Fig. 1. Visualisation of the new XRWIS paradigm showing a) Road Surface Temperature,
b) Road Surface Condition and c) 'Traffic light' salting routes.

The key difference between RWIS and XRWIS is the change from a reliance on measurements to an increasingly high resolution modelling approach. Instead of running a model for a handful of outstations across a network, the model can now be run for thousands of sites just meters apart. This is how the maps are produced in Fig. 1 – these consist of point data and not the line data which is how the visualisation appears. This new approach has been facilitated by the recent proliferation of geomatics technology and increased computer power. No longer are surveys limited to just thermal measurements, it is now possible to measure many geographical parameters (e.g. altitude, sky-view factors, screening, aspect, slope etc) during a single geomatic survey. It is this increase in geographical data that has ultimately enabled the development of route-based forecasting techniques.

However, is the current resolution of route-based forecasts sufficient? Forecasts are now typically provided for points at a 50m resolution along the highway network. This may first appear as information overload, but even with a 50m resolution, thermal singularities caused by katabatic drainage or bridge decks may fail to be captured in the survey. Fortunately, this can be accommodated in the new paradigm as surveys can be increased to cover every 5m of road, or better, if needed. However, it does raise the question of how fine does the resolution need to be? When conducting any survey (whether thermal mapping or a XRWIS geomatic survey), there is always the factor of repeatability. It is impossible to survey the exact same point twice [2], and therefore it is very difficult to systematically survey a road to cover the full geographical variation around the road network. To highlight this point, this paper presents variations in RST and RSC at a different scale; the cross profile.

2. CROSS PROFILE ROAD SURFACE TEMPERATURE DIFFERENCES

It is not unusual to find variations in excess of 10°C in RST around a road network [12]. This variation can be mostly explained by variations in geography and other parameters (Table 1). The influence of all these parameters are modelled in a route based forecast.

Table 1. Parameters controlling road surface temperature [16].
Parameters in italics are the factors controlling variations widthways across the road profile.

Meteorological	Geographical Parameters	Road Parameters
Solar radiation	Latitude	Depth of construction
Terrestrial radiation	Altitude	Thermal conductivity
Air temperature	Topography	Thermal diffusivity
Cloud cover and type	*Screening*	Emissivity
Wind speed	*Sky-View Factor*	Albedo
Humidity / dew-point	Landuse	*Traffic*
Precipitation	Topographic exposure	

When dealing with the cross road profile, many of these parameters can be assumed constant. For example, there will be negligible changes in altitude and road construction across the road profile. However, some parameters will vary markedly. Notably, these are sky-view factors and screening (particularly in urban environments) as well as variations caused due to traffic. Although, this reduces the magnitude of the variations, it is not impossible to find variations in surface temperatures of the order of 2°C across the carriageway [9,11].

2.1 Sky-View Factors & Screening

The sky-view factor (SVF) is a dimensionless parameterisation of the quantity of visible sky hemisphere at a location. When SVF is unity, the site is very exposed and subject to increased radiative cooling at night. Conversely, the same sites receive increased levels of direct beam solar radiation in daylight hours as there are no shading / screening effects. As a result, SVF is the dominant control on RST [6] and it's inclusion as a parameter derived from either fisheye imagery (Fig. 2a), or GPS proxy techniques, forms the basis of XRWIS [2]. Unlike many other geographical parameters, SVF is highly spatially variable. For example, in a rural environment where there are trees encroaching into the sky-hemisphere directly over the road, the SVF (and thus RST) will vary significantly over even the smallest of areas (Fig 2b). A similar effect is noted in urban canyons where the SVF will vary depending on your location in the profile of the canyon (Fig. 2c). In the example provided, SVF can cause RST to vary by nearly 3°C. This has significant implications for how to conduct thermal or geomatic surveys. Ideally, these should be conducted in the centre of the road in urban canyons (to measure the maximum SVF and therefore, lowest RST), but it is not always practical to do this.
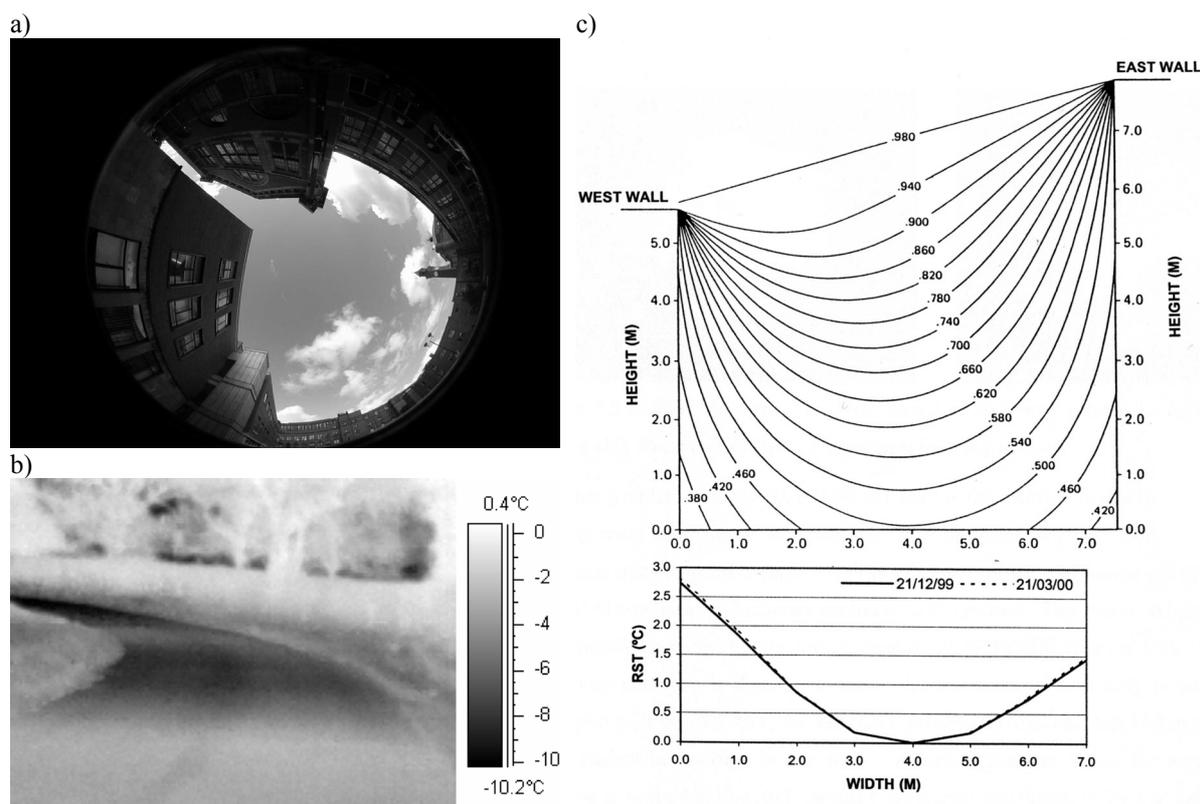

Fig. 2. a) Sample fisheye image from which sky-view factors and screening effects can be derived, b) Thermal image showing the variation of RST in relation to shading from trees (17/02/2008) and c) Variation of SVF in an urban canyon and resultant effect on road surface temperatures in stable conditions (adapted from [13])

The thermal image shown in Fig. 2b was taken at night under stable conditions and underneath a tree shaded section of road. Just beyond this screened section, cold sections can be clearly identified which correspond to clearings directly overhead in the tree canopy. Care must be taken when interpreting this image as the coldest pixels (i.e. -10.2°C) shown on the legend are actually measurements of the cold sky hemisphere in gaps in the tree canopy. Also, the image is not corrected for the effects of varying anisotropy or emissivity, so there will be variations of temperature apparent which are due to the heterogeneous nature of materials and surfaces in the image (this is true for all thermal images used in this paper).

2.2 Traffic

The most important and widely researched parameter concerning cross profile RST variations is traffic. Traffic modifies RST via a number of processes which are highlighted in Fig. 3. Of these processes, the most important are the addition of heat to the road surface via sensible heat and moisture fluxes from the engine as well as frictional heat dissipation from the tyres [4,10].
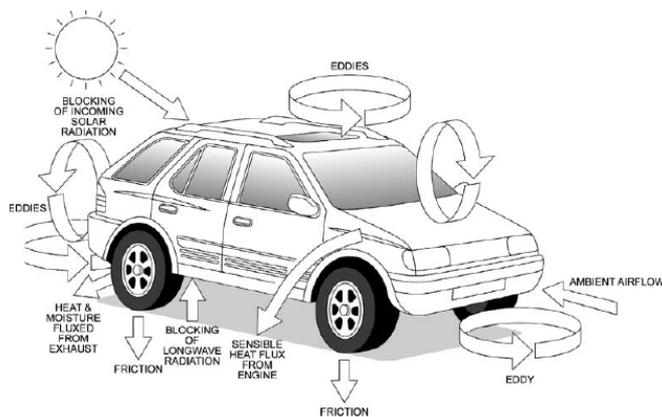
Fig. 3. Schematic illustration of the impact of traffic on RST. *Taken from [4] Copyright Royal Meteorological Society. Reproduced with permission. Permission is granted by John Wiley & Sons Ltd on behalf of RMETS.*

Although traffic effects are very difficult to model, they have a general cumulative effect of promoting increased RST in heavily trafficked areas. For example, during the early morning peak commuting period, RST in Stockholm were 2°C warmer than in the suburbs [9]. This study was unusual as it is much more common to isolate traffic effects by studying multi-laned roads. A number of studies have been conducted, but the general trend is that differences of between 1°C and 2°C are not uncommon between inside and outside lanes [7,11]. Thermal mapping techniques have also been used to systematically survey each lane of a major road for comparison with actual traffic count data [4]. An example of the boxplots derived is shown in Fig. 3 and indicates the systematic nature of the temperature variations across the road profile.
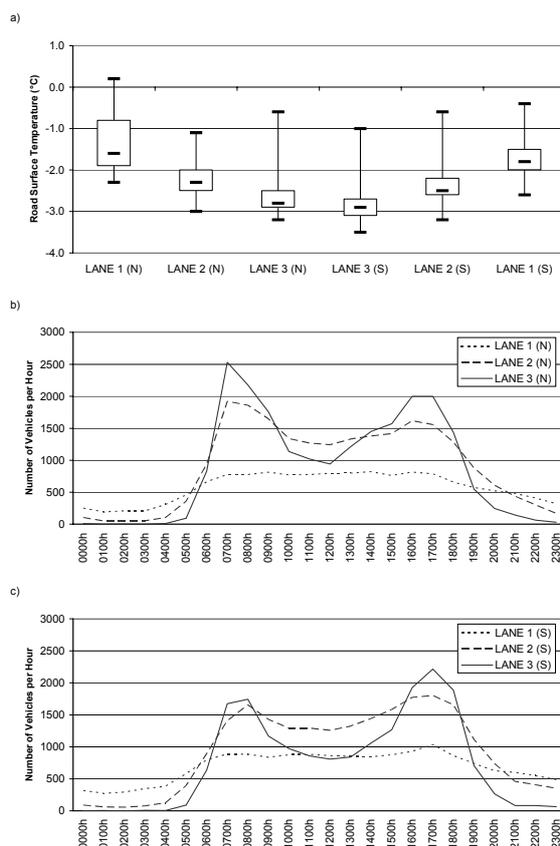

Fig. 4. Traffic and RST for a weekday night (26/02/04) under high atmospheric stability, depicting (a) boxplots showing the distribution (min, lower quartile, median, upper quartile and max) in RST along the study section for each lane of the M5 motorway; (b) traffic on the northbound carriageway preceding the survey; and (c) traffic on the southbound carriageway preceding the survey. *Taken from [4] Copyright Royal Meteorological Society. Reproduced with permission. Permission is granted by John Wiley & Sons Ltd on behalf of RMETS.*

However, these previous studies all have the same sampling limitations; they all use point measurements of data. Even thermal mapping studies (e.g. [4]) are limited in this respect by the resolution of the thermal mapping technology (i.e. 20m). The sampling will typically have been completed in the centre of each lane, so there will be no evidence of the influence of tyre tracks, or lesser trafficked areas to the edge of the profile.

An alternative technique to provide a snapshot of the variations is to use a thermal imaging camera. This can be easily mounted on a motorway gantry from which data can be readily collected of the thermal variation of the road profile. Data was collected under extreme conditions (high atmospheric stability) in the early hours of 14/02/2008. Two camera angles were used; a wide photo showing both carriageways (Fig. 5a) and a close up of the southbound carriageway (Fig. 5b). The influence of traffic can be clearly determined in each image.
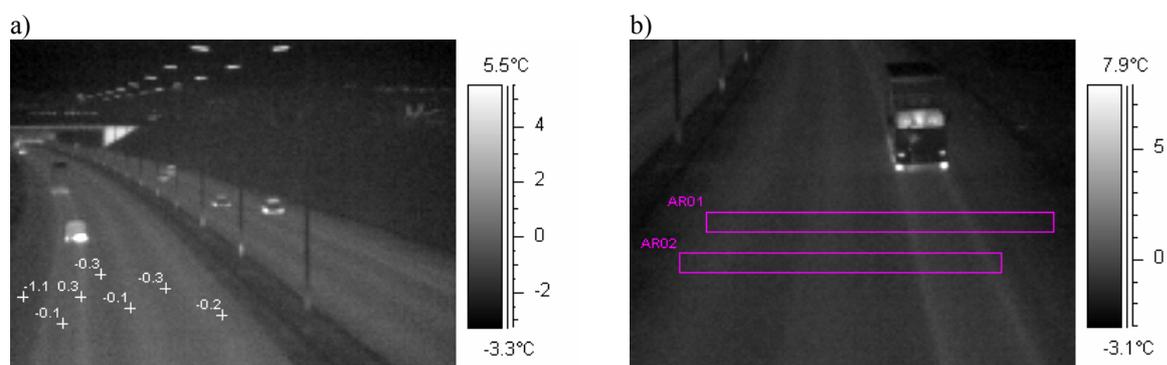

Fig.5. a) Thermal image of the M5 motorway showing spot temperatures on the northbound carriageway and b) close up of the southbound carriageway from which tyre-tracks are clearly evident (14/02/2008). AR01 and AR02 are reference areas used for statistics.

Spot temperatures of various pixels can be easily extracted from thermal images. By using this approach, a quick and easy approximation of the surface temperature in an area can be obtained. Several spot temperatures have been used on Fig. 5a to provide an indication of how the temperature varies across the three lanes of the highway as well as the emergency hard shoulder (far left). Although, temperature differences in the image can be easily identified (e.g. the hard shoulder is 1°C colder than the centreline of the inside lane and 1.4°C colder than the tyretrack on the centre lane), simple spot measurements provide an inadequate sample of measurements to draw any valid conclusions regarding the cross road profile. Instead, an alternative methodology is used which samples sub-sectional areas across the carriageway. In Fig. 5b, two areas have been used for analysis. AR01 covers the entire carriageway (including the hard shoulder) where as AR02 excludes the hard shoulder. The summary statistics are shown in Table 2.

Table 2: Summary statistics of the analysis areas defined in Fig. 5b.

	No of Pixels	Minimum	Maximum	Difference
AR01	3750	-2.2°C	-0.1°C	2.1°C
AR02	3480	-1.4°C	-0.1°C	1.3°C

Interestingly, the magnitude of the results for AR02 (without the hard shoulder) are comparable to previous studies [4,7,9,11]. However, the difference is slightly higher in magnitude than the results shown in Fig. 4 which were taken from the same stretch of highway under similar extreme conditions. This can be explained by the more inclusive sampling strategy which will ensure all variations (e.g. tyre-tracks) are sampled. These are difficult to take into account of when using thermal mapping techniques. However, the major difference in this study is the inclusion of the hard shoulder. This increases the temperature difference experienced across the road cross profile to 2.1°C which is a significant variation. The hard shoulder theoretically has zero traffic flow as it is only used in an emergency and therefore, the temperatures measured there are representative of what the temperatures would typically be across the carriageway without traffic effects.

3. CROSS PROFILE ROAD SURFACE CONDITION DIFFERENCES

The winter maintenance engineer is not exclusively interested in RST as the presence of moisture also needs to be forecast to determine whether or not ice will form on the road surface. RST and RSC are inherently related, and the presence of traffic here can also have quite an effect.

a)
b)

Fig.6. a) Differential drying on the E4 highway north of Gävle, Sweden (approximately 60.5°N); a) shows the effect of how heat fluxes from traffic dry the road surface on the heavily trafficked inside lane and b) Seepage across a minor road in the UK.

Figure 6a shows the differential drying of a road surface on a multi-lane road in south-east Sweden. The drying evident on the inside lane of this image is caused due to the effect of traffic processes shown in Fig. 3. In the same way as increased surface temperatures are evident on the more heavily trafficked inside lanes, it is here where the effects are more apparent where the additional heat provided by traffic is sufficient to promote drying on the inside lane [1]. Figure 6b provides an alternative example of variations in RSC across the road surface. This is the reverse of the situation in Fig 6a caused by traffic travelling over a wet section of the road (i.e. seepage) and carrying this moisture down the carriageway for several hundred metres. Such variations in RSC are difficult to quantify but can pose a considerable problem for winter maintenance engineers. Although roads may be forecast to remain dry throughout the night, there will be seepage points that require treatment. Furthermore, wet road surfaces are often the coldest sections of road due to the increased latent heat loss from the wet road surface. This leaves these sections of road prone to increased slipperiness under marginal conditions.

4. DISCUSSION & CONCLUSIONS

The case studies provided in this paper have shown how RST and RSC can vary considerably across the road profile. The results of this have many implications. The last couple of decades have seen a gradual increase in the spatial resolution of road weather forecasts, but what is the ideal resolution? The original point outstation network was clearly inadequate and route-based forecasting has started to address this problem. However, what scale of route-based forecasting should be used? Although 50m between survey points appears to be the standard, this is only just sufficient to cover most thermal singularities and hence, there is some justification in increasing this resolution to 10m or better. Even then, it is unlikely to capture the full variation of RST and RSC experienced across the network. Furthermore, how can we take into account the differences in the cross road profile? Are these variations just as important? Indeed, these ideas can be taken a stage further, what about variations at the sub-metre scale? These can be quite considerable (Fig 7a).

Fig. 7a would indicate that it is not impossible for RST to vary by up to 3°C across just a few centimetres. However, care needs to be taken on this interpretation as there is a loose chipping to the top right of the scan, which being separate to the pavement, is considerably cooler than its surroundings. However, by taking a representative area of the pavement (AR01: approx 5cm by 20cm), variations of the order of 1.6°C are still apparent. This is comparable to the results found of RST variation on multi-laned roads (e.g. [4,11]). The pertinent question to ask is - what scale is really necessary? Measuring and modelling to the sub-metre scale is clearly impractical, but the thermal differences encountered are not insignificant. Perhaps a scale of 1m is not unrealistic in the future as this will also take into account any cross road profile differences.
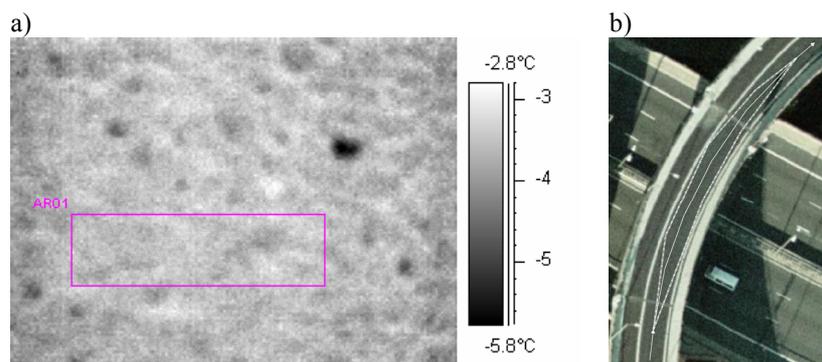
Fig. 7. a) Close-up thermal image of approx. one square foot of road surface (loose chipping top right provides scale) and b) possible variations away from the centreline of a cornering vehicle.

These findings also present a problem for current surveying techniques. It has been shown that large quantifiable differences exist in both RST and RSC across the road profile. Unfortunately, both thermal mapping and route-based forecasts depend on a survey vehicle taking point measurements around the road network. The repeating of surveys can give confidence in the accuracy of measurements, but there are many errors involved in spatial joining surveys for comparative analysis [5]. Furthermore, it is impossible for the same survey vehicle to survey exactly the same route on two occasions. There will be instances where the vehicle needs to change lanes to overtake or will corner at a slightly different angle (Fig. 7b). These will produce erroneous measurements as the vehicle will deviate from the warm centreline onto the colder sections between lanes, perhaps indicating the false existence of a thermal singularity. Therefore, how can current measurement techniques be improved to account for these variations? Are new techniques required? Perhaps there is a role for video thermal imaging of road networks. This is not impossible and has indeed already been piloted on the railway network [3].

Returning to the problems caused by inconsistent routes taken by surveying vehicles, this is symptomatic of not just surveyors, but drivers as a whole. Fig. 7b shows three different ways of negotiating a motorway corner. As this paper has shown, each route will present the driver with a different combination of RST and RSC. If road-weather forecasts are based on centreline measurements, then there is a danger that the highway engineer will be effectively using an 'optimistic' forecast. For example, Fig. 4a clearly shows that the hard shoulder is of the order of 1°C colder than the main carriageway. Should this be taken into account in forecasts? On a marginal night, the forecast may indicate that the main carriageway remains above freezing and so the decision is made not to treat the network. However, whilst the heavily trafficked lanes are above freezing, just two metres away on the hard shoulder, the road has fallen below freezing and is now slippery.

Under these circumstances, the driver of a vehicle that deviates onto the hard shoulder or negotiates a corner away from the centreline is being put at risk and could be subject to an accident. Does the winter maintenance engineer have a duty of care to protect that motorist? In an environment of increasing litigation, the answer to this question is yes. The downside to this is the financial and environmental burden of overtreating the network and it is for this reason why maintenance engineers still express an interest in average / median RST and RSC rather than minimums.

Overall, a case can be presented to take measurements and to fine tune road weather forecasts to produce a forecast for the worst case scenario encountered on the cross road profile. Only then can all motorists be protected. This approach not only has implications for surveying techniques as already discussed, but also for road weather models. The influence of traffic is often cited as an important parameter to include in route-based forecasting [2,4], however, due to the difficulties of modelling such effects, the general approach to including traffic in road weather models is by means of a simple parameterisation [6]. There is now a growing research effort to model these effects more closely [10,14]. However, is this the correct approach? Can a case be made where traffic parameterisations are not included in route based forecasts? By using this methodology, the worst case scenario found on the cross road profile will be accounted for. Admittedly, this will lead to increasingly pessimistic forecasts and more expensive winter maintenance budgets but are these justified by increasing numbers of lawsuits?

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