Parametrising road construction in route-based road weather models: Can ground penetrating radar provide any answers?

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Abstract

There has been much research over the past three decades showing how road surface temperatures are influenced by a wide range of meteorological, geographical and road infrastructure parameters. Rapid advancements in the processing capabilities of computers over the past 10 years has pioneered research into new methods for better parmeterising some of the key variables influencing road surface temperature in road weather forecast models. This paper focuses on road construction and investigates an alternative methodology for collecting road infrastructure data via ground penetrating radar surveys. This approach has the potential to allow high resolution modelling of road construction and bridge decks on a scale previously not possible within a road weather model, but it appears that significant future research will be required to unlock the full potential of the technology.

1. Introduction

Route based road weather forecasting techniques (e.g. XRWIS: neXt generation Road Weather Information Systems) are increasingly becoming the standard methodology for winter maintenance decision making by the highway industry in the United Kingdom. The aim is to provide the highway engineer with an online map where the salting routes are colour coded depending on the treatment required. The result is the potential for savings to be made by treating only the routes which fall below the 0°C threshold (Chapman & Thornes, 2008). Route based forecasting differs from traditional forecast techniques as it does not rely on thermal mapping to make spatial temperature interpolations between road weather outstations. Instead, XRWIS models road surface temperature and condition on a route by route basis by considering the influence of the local geography and infrastructure on the road surface (Chapman *et al*, 2006). The full suite of parameters utilised by XRWIS are shown in Table 1.

Table 1 Parameters controlling road surface temperature (Thornes & Shao, 1991b)

Meteorological	Geographical	Infrastructure
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	Bridges

The incorporation of all these parameters in a high resolution model has largely been enabled by rapid advances in technology. Indeed, the recent proliferation of geomatics technology and increased computer power have ultimately enabled the development of route-based forecasting techniques (Chapman & Thornes, 2008). However, it has not been possible to measure all the required geographical and infrastructure parameters at the spatial scale demanded by a route based forecasting model. One parameter which has been particularly problematic is how to measure the variations in road construction around the road network. As a result, this is currently parameterised in route-based forecasting models. This paper investigates how Ground Penetrating Radar (GPR) could possibly be used to better inform the model regarding variations in road surface construction around a road network.

2. Road Infrastructure

2.1 *Road Construction*

Chapman *et al* (2001) showed that variations in road construction were a significant factor controlling road surface temperature (Figure 1). However, the parameterisation of road construction has always been problematic and is mostly a result of a paucity of good data. Standard road construction profiles exist, but these are subject to change over time as a result of maintenance regimes. Indeed, confidence in the make-up of the road construction can only really be identified by coring the road section under study. However, the point nature of coring makes it unsuitable for use over large areas.

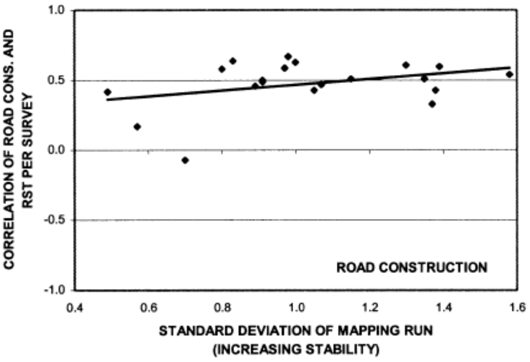

Figure 1: The influence of road construction for RST prediction at different levels of atmospheric stability (Chapman et al, 2001)

The successful delivery of a route based forecasting service relies on the accurate parameterisation of road construction at every forecast point around a route. The first generation of route based forecasts fall short in this respect since some of the parameterisations they use are based on ordinal classifications which fail to account for the full variation in geography and road infrastructure around a route (Hammond *et al*, 2010). The current parameter used in *XRWIS* is that of Road Type (Table 2) and originates from the Thornes (1984) heat balance model. In a study to predict ice formation on motorways in Britain, Thornes (1984) modelled the road heat flux beneath the surface based on a five zone flexible pavement that simulated the road construction at a motorway study site. However, to add a spatial component to the model, there was a need to develop similar profiles for other classes of road found in the UK. Chapman *et al* (2001) did this by making subtle changes to the materials and thermal properties of the profile to represent different road types (Table 2).

Table 2: The materials and thermal properties of the ordinal road construction profiles used in XRWIS. Note:the thermal diffusivity of asphalt, concrete and soil is assumed to be $0.7x10^{-2}cm^{2}sec^{-1}$, $1.2x10^{-2}cm^{2}sec^{-1}$ *and* $0.1x10^{-2}cm^{2}sec^{-1}$ *respectively (Chapman et al, 2001)*

Depth (cm)	Motorway (1)	A-Road (2)	B-Road (3)	C-Road (4)
	Materials			
0 - 4.5	Asphalt	Asphalt	Asphalt	Asphalt
4.5 – 9	Asphalt	Asphalt	Asphalt	Concrete
9 – 18	Asphalt	Asphalt	Concrete	Concrete
18 – 36	Concrete	Concrete	Concrete	Concrete
36 – 72	Concrete	80% Concrete 20% Subgrade/soil	50% Concrete 50% Subgrade/soil	Subgrade/soil
Over 72	Subgrade/soil	Subgrade/soil	Subgrade/soil	Subgrade/soil
	Average thermal conductivity			
	$3.9x10^{-3}$cal cm^{-1} sec^{-1} °C	$3.5x10^{-3}$cal cm^{-1} sec^{-1} °C	$2.9x10^{-3}$cal cm^{-1} sec^{-1} °C	$2.1x10^{-3}$cal cm^{-1} sec^{-1} °C

The modified road profiles enable the spatial variation in heat fluxes beneath the road surface to be modelled simplistically in a road weather forecast model. However, whilst this was an acceptable first approximation, the parameterisation of sub-surface temperatures based on an ordinal classification lacks the sophistication exhibited by other components of the system.

2.2 *Bridge Decks*

Bridge decks add further complexity to the issue. The sudden change in construction from a standard road surface to a bridge deck of shallower construction can often result in a thermal singularity where the road surface temperature can be significantly lower. As a result, local authorities often commission high resolution thermal mapping of such areas of the road network to inform them of ice risk on bridges.

The methodology outlined in section 2.1 also fails to take into account the significant impact of bridge decks. The original methodology used for this relies on the manual identification of bridges from 1:50000 maps. However, there is some potential to use automated algorithms in GIS for this task. For example, a query can be used to identify all road sections crossing water courses or other roads. Once identified, any forecast point which is located on a bridge deck can have the construction profile modified accordingly.

With respect to modelling, specific construction data is rarely available for all bridges, and hence, often the road classification is lowered by a category to account for the shallower construction encountered on bridge decks. Whilst such a process may be a cost effective solution, it is clearly too simplistic since it fails to account for any variations in bridge construction. Furthermore, it fails to account for smaller bridges that may not appear on maps, missed by human error, or conflict automatic GIS detection techniques.

3. Ground Penetrating Radar

Ground Penetrating Radar (GPR) is a non-invasive geophysical technique that can be used to detect electrical discontinuities in the shallow subsurface (<50m) by generation, transmission, propagation, reflection and reception of discrete pulses of electromagnetic energy in the megahertz (MHz) frequency range (Neal, 2004). GPR technology was first used on roads in the mid-1970s when tests were performed by the US Federal Highway Administration (FHWA) on the feasibility of using radar in tunnel applications (Morey, 1998). In 1985 the first vehicle mounted GPR system for highways was developed under a FHWA contract, and since led to a rapid expansion in the use of GPR technology for evaluating subsurface conditions for transportation facilities. From the mid-1990s onwards, GPR has primarily been used for road layer thickness estimation and the identification of moisture accumulation within road layers. Accurate predictions of road layer thicknesses provide important data for roadway management systems since they are needed for overlay design, quality control and for structural capacity estimation of existing roads to predict their remaining serviceable life (Al-Qadi & Lahouar, 2005).

In road applications, the GPR technique is based on the principle of sending a short electromagnetic pulse through an antenna to the road surface and then recording the reflected pulses from the surface and any subsurface layer interfaces bearing discontinuities in electrical properties. The time difference measured between the reflected pulses, known as the two-way travel time, can be used together with the dielectric properties of the surveyed layer to determine layer thickness using the following equation (Wimsatt *et al*, 1998):

$$d_i = \frac{ct_i}{2\sqrt{\varepsilon_{r,i}}} \quad (1)$$

where d_i is the thickness of the *i*th layer, t_i is the electromagnetic pulse two-way travel time through the *i*th layer, c is the speed of light in free space ($c = 3 \times 10^8$ m/s) and $\varepsilon_{r,i}$ is the dielectric constant of the *i*th layer. The main difficulty in interpreting GPR data for measuring the thickness of road layers is illustrated by Eq. (1). Specifically, if it is assumed that the two-way travel time t_i can be accurately measured from the GPR signal, the dielectric constant of the material within the layer being measured remains unknown. Road layers are typically composed of various construction materials such as asphalt binder, aggregate, air-voids and water, all of which combine to make physically inhomogeneous layers. Since the bulk dielectric properties of an inhomogeneous material are typically a combination of the dielectric properties and volume proportions of the individual components, the dielectric properties of road layers will vary both between layers and within layers depending on the mixtures used. Furthermore, the dielectric properties of road layers are greatly affected by rain and the resulting moisture accumulation within road layers, and consequently their values are usually unknown and are difficult to predict. This problem has resulted in a wealth of research over the past decade focused towards the development of data analysis algorithms for better estimation of the dielectric constant of different road layers (Al-Qadi & Lahouar, 2005; Lahouar & Al-Qadi, 2008). Such algorithms however are only necessary in applications requiring high levels of accuracy, such as structural capacity estimation, and are beyond the remit of a pilot study such as this, where the use of predefined values from the literature will suffice.

Data collected during a GPR survey is typically displayed as a trace (Figure 2a). This shows the travel time of the electromagnetic pulse at a set location. Each inflexion in the trace represents a discontinuity where there is potentially a change in construction and therefore a change in thermal properties. Over the course of a survey, traces are obtained at a fixed spatial resolution which allows a radargram to gradually be built (Figures 2b & 2c). These show a cross-sectional view of the subsurface, where the magnitude of reflected pulses from the surface and any subsurface layer interfaces are plotted against their two-way travel time to reveal a cross-sectional view of discontinuities / layers in the subsurface.

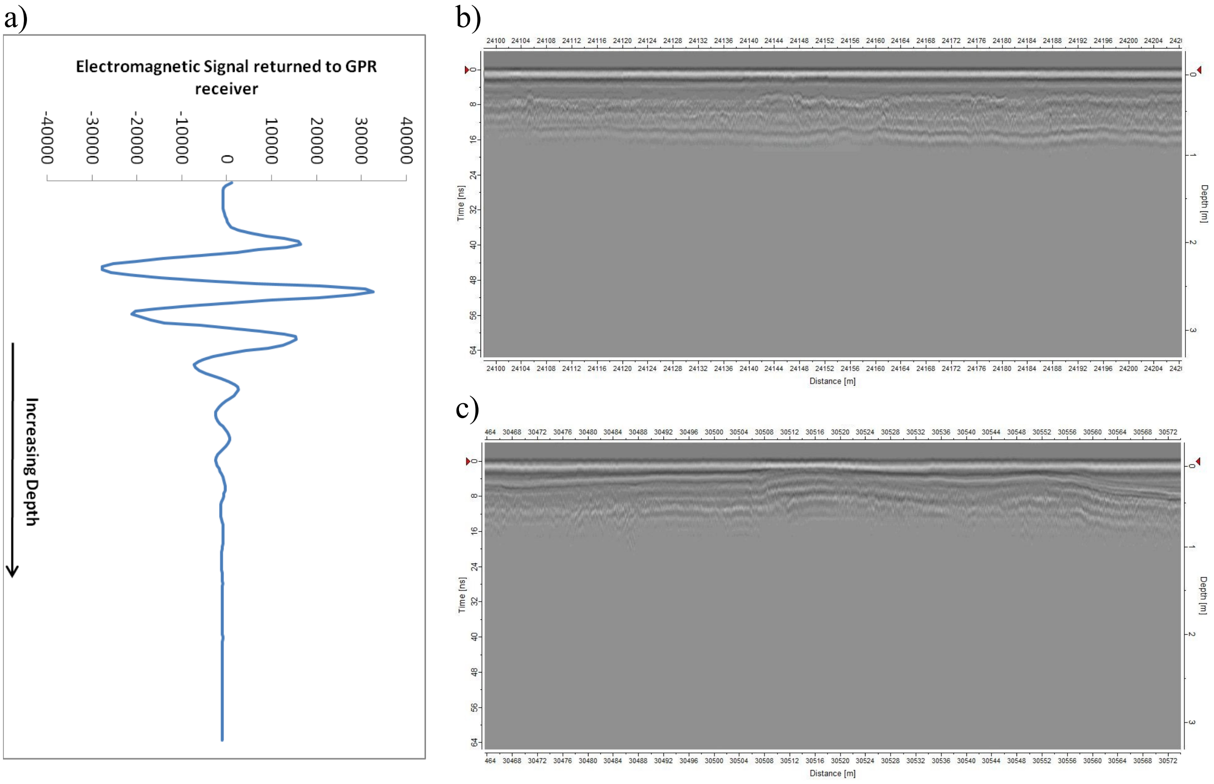

Figure 2 a) Sample GPR Trace and b) radargram collected on a motorway section and showing deep and uniform road construction and c) radargram collected on a minor c-road showing less uniform, shallower construction.

4. Study route and methodology

To investigate the potential use of GPR data for modelling road construction in a route based forecast model, GPR surveys of a mixed urban and rural study route in Birmingham, UK (Figure 3a), were undertaken. A Malå RoadCart unit was used which utilises a shielded 500Mhz low frequency antenna (Figure 3b), designed for high speed GPR measurements on roads. The study route, which traverses through Birmingham city centre before passing through the south-west Birmingham suburbs and north Worcestershire countryside, is part of a larger ongoing research project and was chosen for this pilot study due to the large amount of thermal mapping data that already exists for the route. Variations in UK Road Types around the study route are shown in Figure 3a, ranging from motorway to A-roads in the heavily urbanised city centre and more minor roads in the rural and semi-rural areas of the route. On the route are three significant bridge decks where roads cross over the M5 motorway.

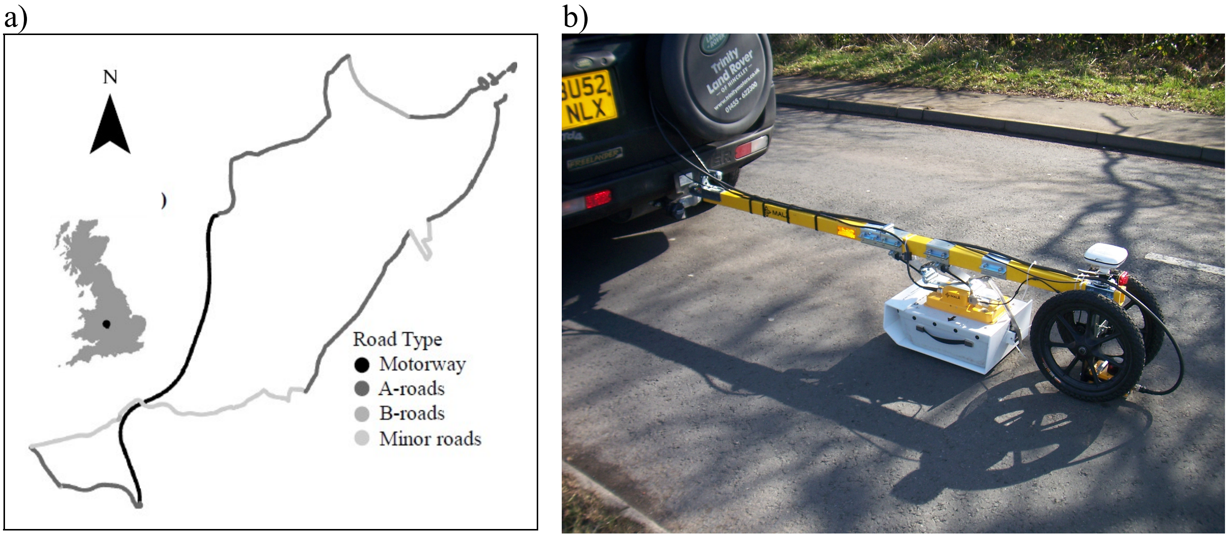

Figure 3 a) Study route traversing the south-western suburbs of Birmingham, UK and b) equipment setup showing the Malå RoadCart in action.

5. Identification of bridge decks

As a bridge deck represents (in most cases) a dramatic change in construction, the first stage of this study was to investigate if GPR had the capability to detect the three known bridge decks on the route. The radargrams of these three bridges are shown in Figure 4 (a-c).

Figure 4a shows a relatively small bridge deck located on the M5 motorway. Typically this bridge produces a thermal singularity under stable conditions of about -0.3°C when compared to the adjoining carriageway. Changes in the reflected GPR signal are clearly visible over the bridge section. This signal is a consequence of the air void under bridges which causes multiple direct air waves to be returned rather than the normal reflections from subsurface discontinuities. The same pattern can be identified in Figure's 4b and 4c which show larger bridges crossing the M5 motorway. Indeed, of particular interest in Figure 4c is the clear visibility of the pillars at either side (and in-between) the two carriageways of the motorway. This bridge has an unusual thermal singularity as instead of having lower RST common to most bridges, it is typically +0.3°C warmer in stable conditions than the adjoining road sections. However, this can easily be explained by the presence of frequent standing traffic on the bridge caused by traffic lights at the motorway exit.

Figure 4: Location, radargrams and typical magnitude of the thermal singularity (under stable conditions) of four bridge decks on the study route. ©Crown Copyright/database right 2009. An Ordnance Survey/Digimap supplied service

Figure 4d shows a small bridge that was originally missed when the bridges were manually taken from a 1:50000 map. Again, a bridge signature can clearly be inferred from the radargram and upon inspection of the thermal data, a thermal singularity is present under extreme conditions of the order of -0.4°C. There is actually very little variation of RST on the motorway section and such thermal singularities can be problematic and therefore require identification. These results immediately show that there is some potential of GPR as a tool for locating bridges along routes. It is clear that with minimal processing, bridge decks can be identified in a more objective manner than manual identification from a map.

6. Variations in road construction

Based on the original ordinal classification initiated by Chapman *et al* (2001), GPR should be able to be used to verify the variations in road construction profiles around the route. Indeed, the difference between a motorway and a minor c-road can clearly be seen in Figures 2b and 2c. A relatively uniform construction is evident on the motorway radargram, where significant differences become apparent on the less uniform c-road. Whilst the first and second inflexions in the trace are relatively constant and represent the asphalt top course, there are significant variations evident in the radargram below the top layers. The challenge is to find a methodology which can identify discontinuities and assign them to a material and therefore vary the thermal properties of the profile around a route (e.g. Table 2).

To assign depth values to layers in the GPR data, an inflexion point detection algorithm was written in Matlab. This was applied to each GPR trace to identify peaks and troughs in the electromagnetic waveform, on the basis that each peak or trough above a specified threshold value is the result of a discontinuity in the electrical properties of the subsurface material, and hence symptomatic of a subsurface layer interface. The two-way travel time at each inflexion point was identified and inserted into Eq. (1) to identify the depth of the layer interface, using a standard value of 6.5 for the dielectric constant of each layer. The layer depth values in each GPR trace were then spatially joined to each forecast point along the route using the spatial join feature in ArcMap. The result is an approximation in location of the top three horizons in the road construction profile (Figure 5a)

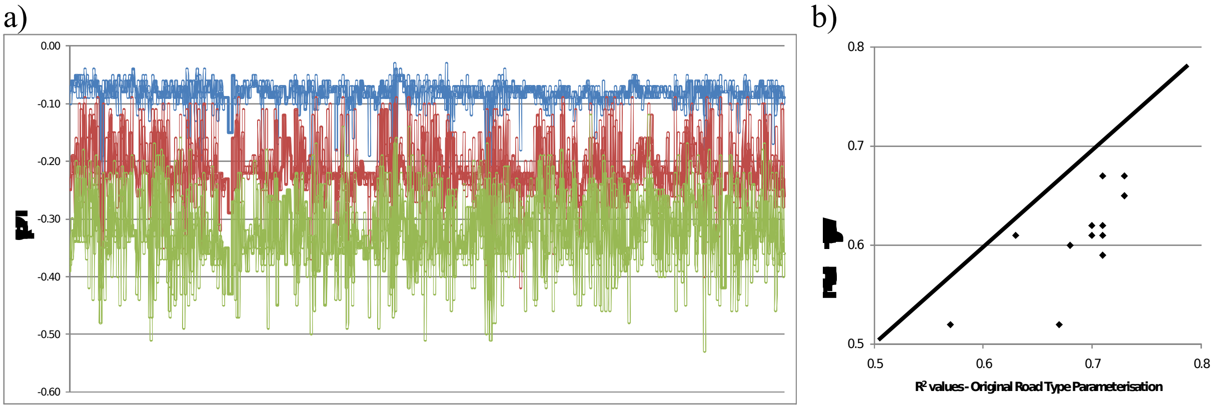

Figure 5 a) Approximate depth of the top 3 asphalt layers around the study route and b) model performance using the new depths versus the old ordinal parameterisation.

In theory this approach should allow for the variation in road construction in the top layers of the profile to be taken into account in a route based forecast, thus removing the need for ordinal categories of road type. However, when the new depth values are used in the model (Figure 5b), the model performance is considerably reduced. Ultimately, this is a direct result of the methodology. In order to produce the transect shown in Figure 5a a number of assumptions needed to be made. To a large extent, this process is unsupervised as little knowledge exists about the profile being measured. Without any ground truth data (i.e. road cores), it is very difficult to account for the true variation in construction (e.g. materials, air voids, water) which would significantly affect the dielectric constant. In reality, the dielectric constant will vary considerably around the route and the initial assumption that a constant value would be adequate appears too simplistic. Furthermore, the data is very noisy. It is currently impossible to tell whether this noise is a consequence of genuine variations in the road construction or whether there are other contributing factors. The nature of the survey equipment is that it needs to hover close to the road with as small an air-gap between the sensor and the surface as possible. It was noted during surveys that this air gap was difficult to consistently maintain and this would have a negative effect on the repeatability of results.

7. Conclusions

This pilot study has shown the potential of GPR for providing additional information for route-based forecasts. In particular, it has been shown to have considerable skill in objectively locating bridge decks around a network. However, initial attempts to calculate the various discontinuities (layers) in the road construction profile have proven to be more difficult. Whilst it appears that the technology has the potential to reveal the full variation in road construction around the route, there is a need for a greater in-depth research programme to ascertain its true potential. Unfortunately, this will be expensive, as such a project would require road coring at a high spatial resolution. However, once the true profiles and dielectric constants are established via adequate ground truth data, then a technique will be in place to fully quantify the variations in road construction around a network. Such an approach should significantly improve the forecasting skill of route based forecasting models.

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