Practical applications of GPR surveys for trackbed characterisation in the UK, Ireland, USA and Australia

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SUMMARY

Zetica's Advanced Rail Radar (ZARR) system is deployed in many countries across the world. The system utilises ground penetrating radar (GPR) to continuously map changes in the thickness and quality of the ballast layer across a network.

Zetica was commissioned by Network Rail in the UK to implement ZARR on a total of 3 inspection trains which between them routinely collect around 20,000km of data per year. Network Rail have reported significant improvements to their track renewals process with a reduction in unnecessary ballast replacement, the application of more appropriate remedial actions and fewer pre-mature failures.

Zetica Rail completed a survey for Irish Rail on the main Dublin to Cork line using their track geometry recording vehicle as the survey platform. The object of this survey was to map changes in the geometry of ballast layers as well as target areas of subgrade erosion, drainage problems and to detect buried structures. The results were combined with track geometry to provide a strategic tool for maintenance planning.

Over 5,000km of rail radar data has been collected and processed to characterize ballast quality for class 1 railroad companies in the USA. The works are designed to optimize maintenance planning by targeting the most contaminated ballast.

ARTC recently commissioned Railtrak Systems working in partnership with Zetica Rail, to collect and process over 1,100km of rail radar data to characterize ballast quality and map subgrade irregularities and formation failure. The data collection vehicle was the AK inspection car and the works were designed to optimize maintenance planning by targeting the most contaminated ballast.

The paper will describe how ZARR is being utilised to achieve impressive cost savings through:

- Accurate prioritisation of problem trackbed,
- Reduction in the number of trial holes required to investigate sites,
- Effective integration of rail radar and track geometry metrics,
- Accurate delineation of the extent of remedial works required,
- Improved quality control measures, and
- A reduction in the number of interventions during the planned life of the ballast.

1. INTRODUCTION

Ballast trackbed foundations are by far the most commonly used around the world. Advantages include fast drainage, ease of maintenance, optimal stiffness and lower cost.

The ballast layer is designed to distribute the loading force of a passing train evenly over the formation layer to preserve a smooth ride. A homogenous ballast layer results in a stable and safe track. Departures from the construction design such as changes in the thickness of the ballast layer and the degree of contamination within the ballast matrix will affect the dynamic behaviour of the trackbed. Contaminated ballast causes an unstable pressure distribution on the subgrade.

Ground penetrating radar (GPR) is a proven technology for solving a variety of problems relating to ballast trackbed condition evaluation [1,4,9]. Zetica's Advanced Rail Radar (ZARR) system is deployed in many countries across the world [3,7,8,9]. The system utilises ground penetrating radar (GPR) to continuously map changes in the thickness and quality of the ballast and deeper trackbed layers across a network.

This paper comprises a short review of practical applications of ZARR technology in the UK, Ireland, USA and Australia spanning the period from 2006-2009.

2. NETWORK RAIL (UK)

Network Rail has been utilising GPR for trackbed inspection for over 15 years. Originally deployment was by hand-held systems scanning only the ballast between the sleepers/ties. Productivities were low and the cost per mile relatively high. Typically less than a couple of hundred miles of track were scanned per year. Nevertheless GPR was considered an effective non-invasive trackbed investigation tool and was included as an approved technology in Network Rails' trackbed investigation standards.

2.1 Background

Zetica was commissioned by Network Rail in 2006 to install its ZARR system on an ultrasonic measurement train as part of an 18 month proving survey during which 16,000km of track was surveyed with a 1GHz and 400MHz antenna arranged in-line beneath the train (Figure 2.1).

Figure 2.1 *UTU3 inspection train showing under-belly mounted GPR antennas.*

The objectives of the work were:

- To map ballast bed thickness and sub-ballast layers where visible and show that train-mounted GPR can deliver at least equivalent quality data compared with hand-held GPR systems (Figure 2.2).
- To routinely provide over 1,600km per month of processed data in customised report formats.
- To demonstrate the reliability and practicality of the system in daily use around a network.

After a successful trial, Zetica was commissioned to roll-out the system to a total of 3 inspection trains which between them routinely collect around 20,000km of data per year at speeds between 55-110kph. A custom web portal was also developed to allow rail engineers to create reports including track geometry for any part of the network and to compare GPR and track geometry data run on run.

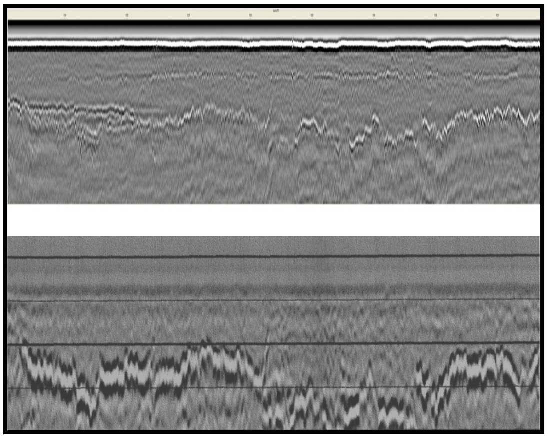

Figure 2.2 *Comparison of a 1/4mi section of hand held GPR data (bottom) collected in 1995 and train-mounted GPR data (top) collected in 2007. The new train-mounted system provides far superior quality data in terms of lateral and vertical resolution and data repeatability. [8]*

2.3 Data examples

Examples of customised reports generated for Network Rail are shown in Figures 2.3 and 2.4.

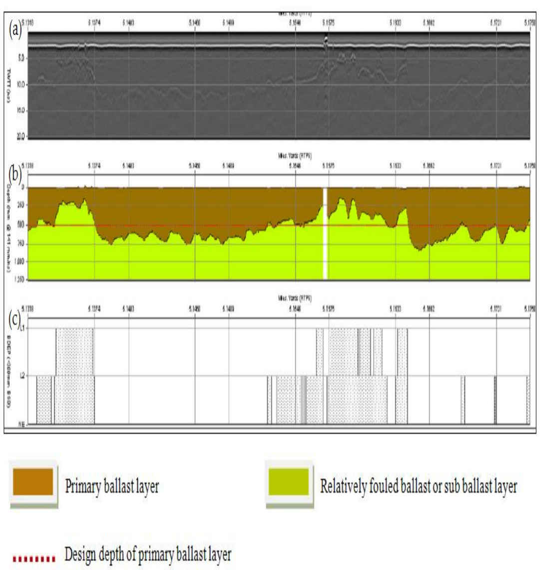

Figure 2.3: *400m of GPR data (a) collected on Network Rail's UTU3 inspection train. Changes in the thickness of the primary ballast layer (b) are very clearly indicated in a 'Manhattan Skyline' plot (c) as deviations from the design depth.*

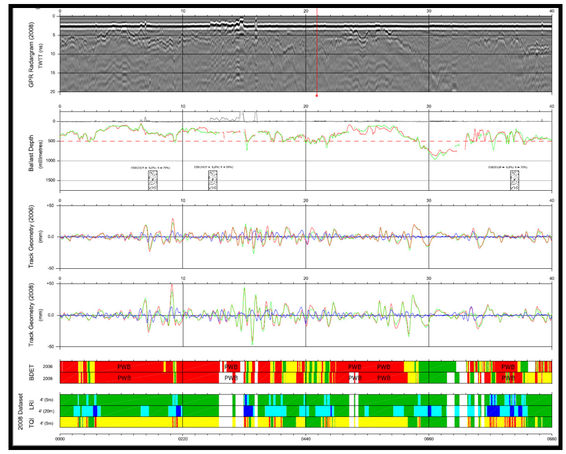

Figure 2.4 *Report with data panels showing (top-bottom) – example radargram, digitized layers for two runs in the center, repeat run track geometry traces (vertical alignment), colour strip charts showing thickness of ballast against defined thresholds for repeat runs, and colour strip charts showing ballast layer roughness and a combined ballast thickness and layer roughness index.*

Compared with ballast monitoring through systematic manual sampling methods, up to 50% of the budget required to investigate sites by hand can be saved by focussing on areas showing significant change only (Figure 2.5). ZARR allows robust planning of site investigation works and reduces the possession duration to complete.

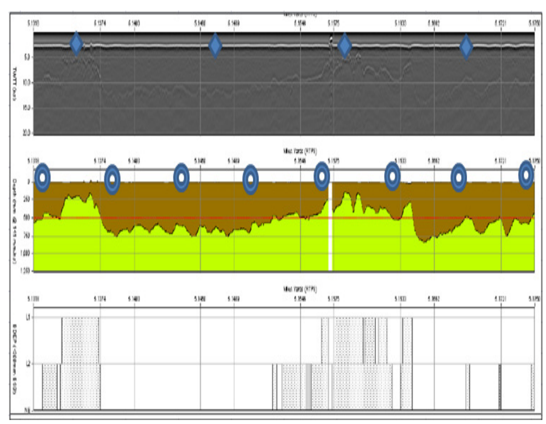

Figure 2.5: *Traditionally a site investigation based on a fixed 50m interval would have resulted in 8 holes (circle symbols) in potentially unrepresentative locations. GPR can be used to target ½ the number of holes (triangle symbols) to sample the trackbed in more representative areas.*

GPR data is collected across the UK network at least once per year on high speed / heavy use track (in some case more regularly) and once every two years on slow speed / low use lines. All data collection, data processing and reporting is now carried out in-house using tooling supplied by Zetica.

2.3 Summary

Network Rail have reported significant improvements to their track renewals process with a reduction in unnecessary ballast replacement, the application of more appropriate remedial actions and fewer pre-mature failures. Current work is being directed at using ZARR to predict rates of return from ballast cleaners and help determine the residual life of ballast.

3. IRISH RAIL

The Dublin-Cork railway line is the longest route in Ireland (272 km), and provides connections to the main gateway cities of Galway, Limerick, Waterford and Kerry. It is the main railway route in Ireland in terms of traffic density, intercity passenger numbers and revenue. The line is currently undergoing a major upgrade.

3.1 Background

Zetica was commissioned to carry out a rail radar survey in 2008 over a total of 530km of the Dublin-Cork line to map the extent of problem trackbed and to rank trackbed integrity issues. This information is being used in conjunction with planned activities such as replacing sleepers or rail, to significantly improve the overall cost-effectiveness of trackbed maintenance.

The objectives of the work were:

- To map ballast bed thickness and sub-ballast layers where visible
- To map areas of the trackbed with poor drainage
- To provide all data (quality and drainage indices, ballast depths etc) in spreadsheet format for easy import to Irish Rail's track management visualisation system
- To recommend targeted borehole locations / trial pits for follow-up investigations

The brief was extended in 2009 to include a review of the data for cable and service detection under track and the development of a new track quality index combining track geometry and radar-derived trackbed quality indices.

A decision was taken to mount the required GPR antennas on the front of Irish Rail's EM50 Track Recording Vehicle (TRV). See Figure 3.1, Alternatives which were considered included mounting the antennas beneath the train or carrying out the surveys on a hy-rail vehicle. The decision to use the EM50 TRV and boom-mounted antennas was based on minimum time on track and the requirement for quickly removable antennas respectively.

Figure 3.1 *Layout of GPR antennas on Irish Rail's EM50 which was deployed at 80kph.*

3.2 Data examples

Examples of customised reports generated for Irish Rail are shown in Figures 3.2 and 3.3.

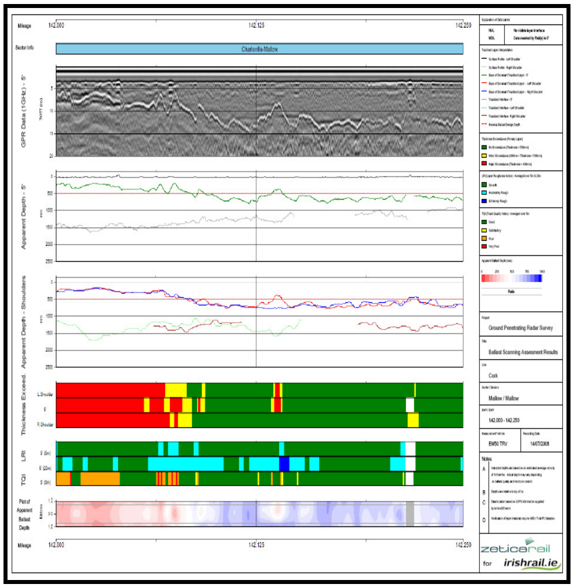

Figure 3.2 *Report with data panels showing (top-bottom) – example radargram, digitized layers in the center, digitized layers over the shoulders, colour strip charts showing thickness of ballast against defined thresholds, colour strip charts showing ballast layer roughness, a colour strip chart showing a combined ballast thickness and layer roughness index, and a contoured map of depth to fouled ballast/formation.*

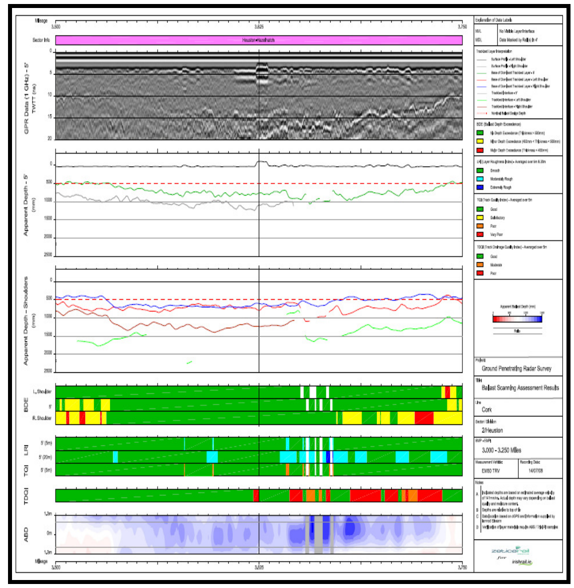

Figure 3.3 *Report with data panels showing (top-bottom) – example radargram, digitized layers in the center, digitized layers over the shoulders, colour strip charts showing thickness of ballast against customer-defined thresholds, colour strip charts showing ballast layer roughness, a colour strip chart showing a combined ballast thickness and layer roughness index, a colour strip chart showing a track drainage quality index and a contoured map of depth to fouled ballast/formation.*

The ballast depth exceedance (BDE) represents a measure of how well the thickness of the primary trackbed layer conforms to a customer-specified design thickness. A minimum ballast thickness is required below the sleepers in order to provide correct support to the track and adequate drainage.

The Layer Roughness Index (LRI) indicates the degree of variance in the thickness of the primary trackbed layer over a specified length (in this case 5m and 20m). The LRI is designed to highlight areas where the thickness of the layer is changing rapidly. Such rapid variations can be an indication of sub-grade failure or wet bed formation.

The Trackbed Drainage Quality Index (TDQI) indicates how well the trackbed is performing in terms of providing adequate drainage and combines layer thickness measurements for the 5' and both shoulders with a relative measure of moisture levels at the interface between the ballast and the sub-ballast.

3.3 GPR-derived trackbed management indices

Useful trackbed management indices were derived to objectively rank trackbed integrity issues and map the extent of problem track. These were provided in spreadsheet format and in *.kml* format for Google Map and Google Earth overlays.

3.3.1 Combined Track Quality Index (CTQI)

The CTQI was derived using a combination of three GPR trackbed indices. The CTQI combines the Ballast Depth Exceedance (BDE) index, the

20m Layer Roughness Index (20m LRI) and the Trackbed Drainage Quality Index (TDQI) for data obtained in the 5' and both shoulders.

The CTQI represents a summation of the three indices, weighted in favour of the BDE:

CTQI = LRI + (2*BDE) + TDQI

It is divided into 4 categories as detailed in Table 1.

CTQI	
Category	Index Range
1	0 - 3
2	3 – 5
3	6 - 9
4	10+

Table 1: *CTQI categories*

3.3.2 QI2 Trackbed Index

The QI2 index combines the GPR-derived CTQI and the Track Geometry Quality Index (QI) in a single index that is designed to highlight areas of track currently suffering from ongoing track geometry problems that may or may not relate to trackbed quality issues and areas of poor quality trackbed that are likely to result in TG quality issues in the future.

As detailed in Table 2 the QI2 index was designed to preserve information on significant track geometry QI defects (Category 1 'Bad' QI anomalies) which may present an immediate 'Safety of the Line' issue.

Other combinations of QI and CTQI categories were ranked according to severity resulting in four categories as detailed in Table 3. Note that the QI2 category matrix is customizable and can be set to flag other combinations of variables as Bad to Poor.

QI2 Category Matrix		GPR-derived CQTI			
		1	2	3	4
Track Geometry QI	1				
	2				
	3				
	4				

Table 2: *2D Matrix used to derive the QI2 Index Categories*

QI2	
Category	Colour
1	Bad
2	Poor
3	Moderate
4	Good

Table 3: *QI2 Index Categories*

The CTQI and QI2 indices were presented as coloured strip charts (Figures 3.4 and 3.5) and as coordinated spreadsheet lists. *Kml* files were also produced for overlay on Google Earth (Figure 3.6).

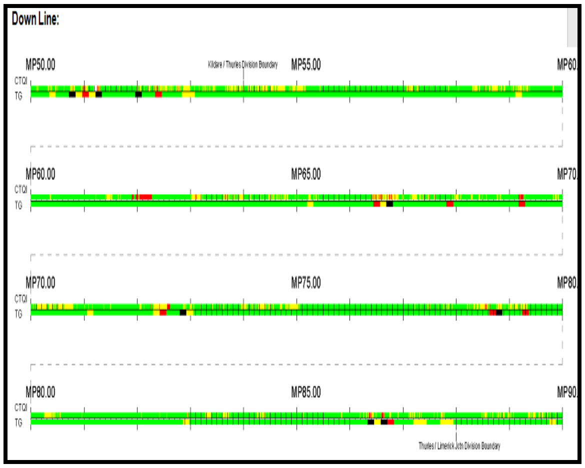

Figure 3.4 *Colour strip charts showing CTQI (top) and TG (bottom) indices averaged over 5m for a 40km stretch of the Dublin-Cork line.*

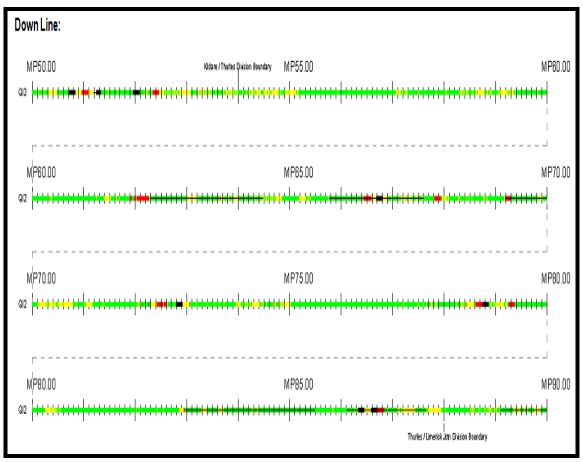

Figure 3.5 *Colour strip charts showing the QI2 index averaged over 5m for a 40km stretch of the Dublin-Cork line.*

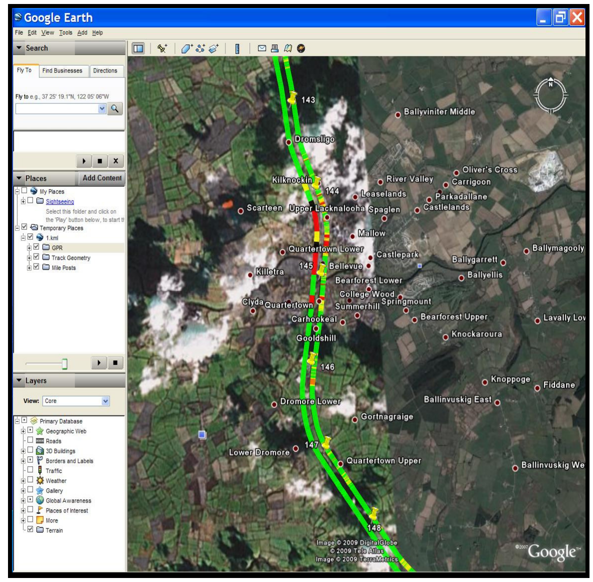

Figure 3.6 *Overlay of CTQI and TG colour strip charts on Google Earth.*

3.4 Summary

The GPR reports and GPR-derived trackbed indices are currently being used as part of a major remediation and renewal programme over the full route. The information is an important tool which is being proactively used to allow focused planning of trackbed remediation works on those areas most in need of rehabilitation. This allows an optimisation of available budgets and is thus a cost-effective tool in the trackbed remediation programme.

Subsequent measurement of track quality following the targeted remediation works to the trackbed, have resulted in significant improvements to the measured track quality.

The information has also been used as part of localised re-ballasting programmes undertaken in advance of warm weather, in those areas that have not yet formed part of the remediation program, to offset the specific safety risks associated with track behaviour in warm weather due to a lack of ballast.

Overall, the undertaking of the GPR survey on the Dublin-Cork line has provided Irish Rail with valuable insights into the condition of the ballast and sub-ballast layers which were previously unknown.

The continuous linearity of the survey and its results allows Irish Rail to manage the Dublin-Cork line on a whole route basis thus ensuring the application of cost effective solutions on a prioritised basis.

4. USA

Over 5,000km has been collected with Zetica's Advanced Rail Radar (ZARR) system to date mainly on the coal lines in the mid-western USA.

4.1 Background

The current mode of data collection utilises three 2GHz antennas mounted on a hy-rail (Figure 4.1). The system is designed to characterise ballast quality with options for adding 400MHz antennas to image deeper formation layers, if required.

Figure 4.1: *Example of hy-rail vehicle deployed at 30-60kph in the USA*

4.2 Data examples

As detailed in Zhang et al [9], Zetica has developed a method to derive a fouling index from the GPR data. The GPR derived Ballast Fouling Index (BFI) categorises the quality of the ballast from severely fouled to clean, similar to Selig's well known Fouling Index (FI) [5]. The most recent groundtruthing exercise carried out by the BNSF in 2009 showed a correlation between the GPR-derived Ballast Fouling Index (BFI) and a laboratory-derived (FI) for 32 samples of better than 87% (Figure 4.2).

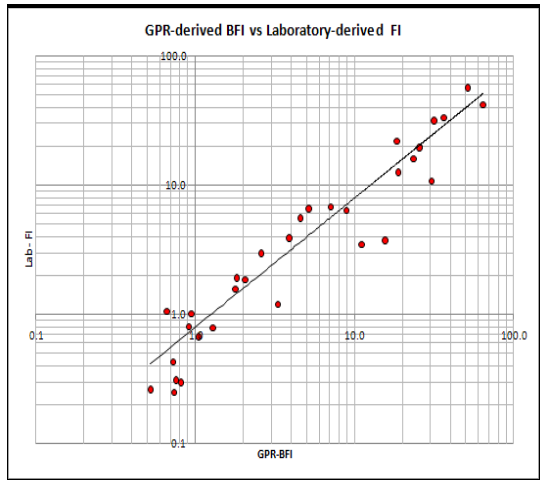

Figure 4.2: *Correlation between GPR-derived BFI and laboratory-derived fouling index.*

The BFI represents a continuous measure of the degree of ballast fouling along each shoulder and centre of the track. BFI data which are typically averaged over 1m or 5m lengths and can be presented in 1D or 2D (Figure 4.3), can be further summarised in statistical charts (Figure 4.4) and maps (Figure 4.5).

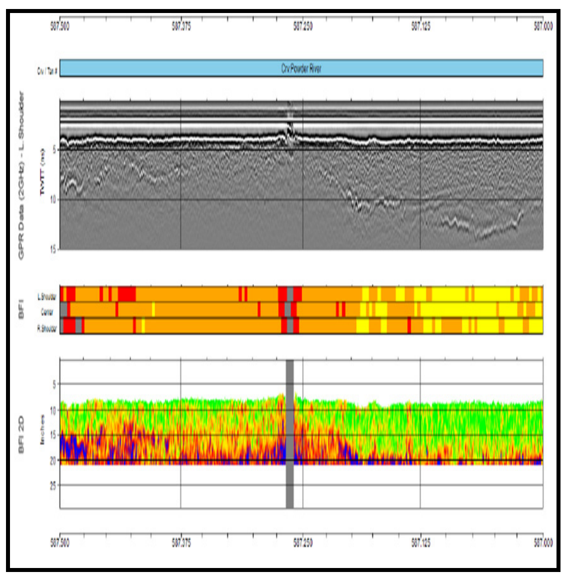

Figure 4.3: *ZARR output showing top-bottom: example radargram, colour strip charts for a 1D BFI averaged laterally over 5m and vertically over 0.4m for each shoulder and the center, and a 2D BFI for the left shoulder. Darker colours represent more fouled ballast.*

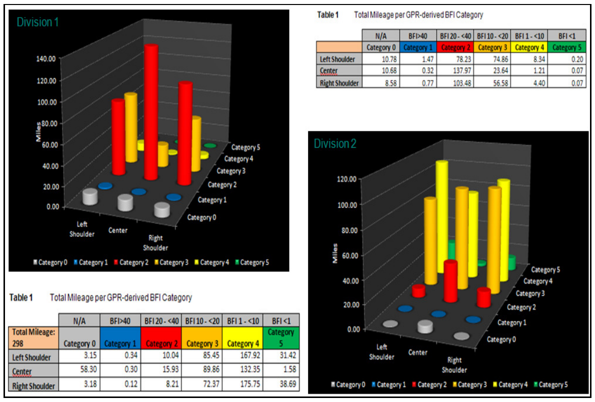

Table 1 Total Mileage per GPR-derived BFI Category

	N/A	BFI>40	BFI 20 - <40	BFI 10 - <20	BFI 1 - <10	BFI <1
	Category 0	Category 1	Category 2	Category 3	Category 4	Category 5
Left Shoulder	10.78	1.47	78.23	74.86	8.34	0.20
Center	10.68	0.32	137.97	23.64	1.21	0.07
Right Shoulder	8.58	0.77	103.48	56.58	4.40	0.07

Table 1 Total Mileage per GPR-derived BFI Category

	N/A	BFI>40	BFI 20 - <40	BFI 10 - <20	BFI 1 - <10	BFI <1
Total Mileage: 298	Category 0	Category 1	Category 2	Category 3	Category 4	Category 5
Left Shoulder	3.15	0.34	10.04	85.45	167.92	31.42
Center	58.30	0.30	15.93	89.86	132.35	1.58
Right Shoulder	3.18	0.12	8.21	72.37	175.75	38.69

Figure 4.4: *In this example Category 1-5 represents relatively very fouled to clean ballast for GPR scans of both shoulders and the centre. One division has a greater proportion of highly fouled ballast (Category 2) compared with the other which has a predominance of moderately fouled (Category 3) to moderately clean (Category 4) ballast.*

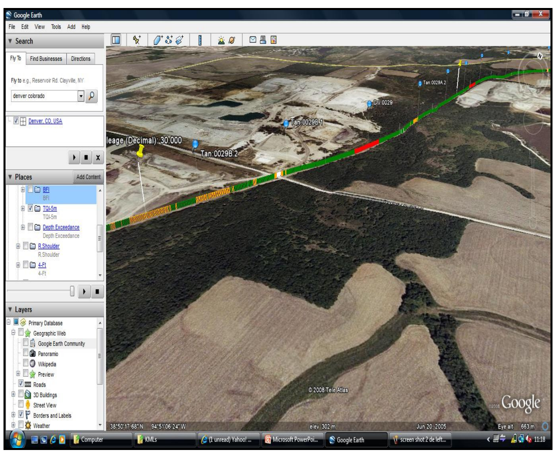

Figure 4.5: *Geographic display of BFI results of a GPR survey using Google Earth*

ZARR has also shown its worth in the USA in analysing the cause of track geometry faults that can result in costly slow orders being imposed on high revenue track. Understanding the presence of perched water or the lateral and depth extent of a subsidence zone across an embankment, for example, can be invaluable in designing an effective remediation program.

4.3 Summary

ZARR is providing an accurate and objective indication of priority areas on networks that require ballast cleaning and is also helping to decide whether shoulders-only need cleaning with cheaper dedicated shoulder cleaners or the whole trackbed needs cleaning with more expensive undercutters.

5. AUSTRALIA

A 1,100km trial survey was recently carried out for ARTC across various parts of their network. These included high tonnage coal lines in the Hunter Valley to the north of Sydney and the main intercity passenger line running from Sydney to Melbourne.

5.1 Background

GPR data was collected using equipment mounted on the back of the ARTC / Railcorp AK Car and an ARTC hy-rail vehicle (Figure 5.1). The aim of the survey was to characterise the overall condition of the trackbed and in particular the degree of fouling within the ballast.

Stage 1 (completed) of the survey summarised ballast fouling conditions along the whole route. A more detailed analysis of the data including derivation of ballast layer thickness and the provision of additional GPR trackbed indices was undertaken on selected areas, totaling approximately 60% of the 1,100km. The GPR-derived BFI was based on the fouling index developed by Selig & Waters [5]. The results were used to determine a list of proposed ballast sampling locations.

As part of Stage 2, actual fouling levels will be determined by sieve testing of materials from the selected sample locations which will then be used to recalibrate the BFI using Ionescu's Fouling Index or similar as part of Stage 2.

Figure 5.1 *Layout of boom-mounted GPR antennas on the AK inspection car (top) deployed at 100kph and a hy-rail vehicle (bottom) deployed at 30kph.*

5.2 Data examples

The results of Stage 1 were presented as track charts detailing ballast fouling exceptions along each of the surveyed routes (Figure 5.2). Exceptions were determined from an analysis of the BFI data for each shoulder and the centre over a specified distance interval (typically 50 – 200m).

Statistical summaries of the distribution of fouling levels for each project area enable engineers to quickly compare the quality of ballast and determine where best to prioritise maintenance resource (Figure 5.3).

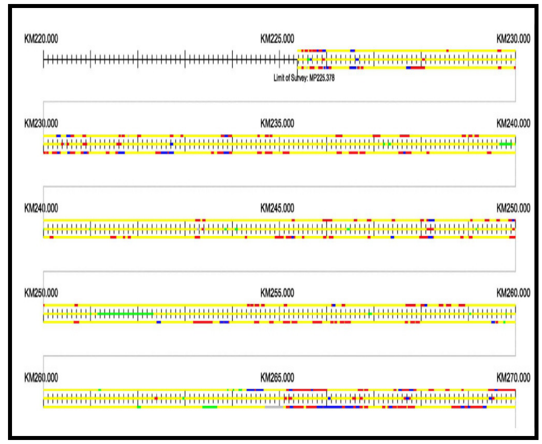

Figure 5.2 *Extract from a BFI exception report showing a track chart with very fouled ballast (dark) to clean ballast (light) areas for the left and right shoulders and the centre over a 45km section.*

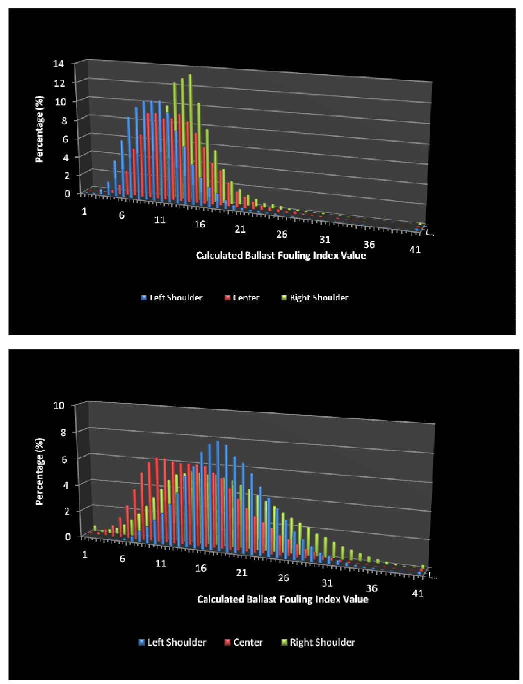

Figure 5.3 *Comparison of two project areas each showing the distribution of BFI-derived fouling levels for both shoulders and the centre.*

5.3 Summary

Initial feedback from the client has been positive. The BFI exception track charts indicate a very good correlation between the location and extent of BFI Category 1 (severely fouled) and Category 2 (fouled) exceptions and visible ‘bog-holes’ (also termed wet-beds or mud spots). Additional Category 1 and Category 2 exceptions, which currently have no visible surface expression, are indicative of incipient bog-hole development and are likely to be considered a priority for future trackbed maintenance.

6. CONCLUSIONS

Significant changes can occur at different stages in the lifetime of a ballast layer under repeated loading. ZARR surveys around the world have shown that monitoring ballasted trackbed with GPR allows decisions to be made on timely and cost effective interventions to extend the ballast life and maintain trackbed. This allows the development of a robust pro-active ballast management strategy and prioritisation between sites which can result in significant cost savings.

Specifically ZARR can be utilised to achieve impressive cost savings through:

- Accurate prioritisation of problem trackbed,
- Reduction in the number of trial holes required to investigate sites,
- Effective integration of rail radar and track geometry metrics,
- Accurate delineation of the extent of remedial works required,
- Improved quality control measures, and reduction in the number of interventions during the planned life of the ballast.

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