Aurizon Network Pty Ltd

Ballast Contamination
Scoping Study

March 2013

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Version Control

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Executive Summary

Background

Aurizon Network ('Aurizon') manages the below rail infrastructure of the Central Queensland Coal Network ('CQCN'). The CQCN is an element in the pit to port supply chain that enables the coal from the Bowen Basin to be transported to the export terminals at Bowen, Mackay and Gladstone.

An issue for all stakeholders in the supply chain is the impact of coal spillage on the below rail asset. Contamination of the track system by coal particles leads to a significant reduction in the engineering performance of the track system.

It is in the interest of all stakeholders to have an understanding of the nature of contamination that can lead to a compromised track system; and consequently work towards an achievable optimum strategy to address the issue.

The Brief

Evans & Peck's task was to scope the interrelationships that lead to a compromised track structure and make comment on the ability to isolate aspects related to coal spillage through various causes.

Methodology

The three stage approach has been taken:

- Conduct research of available literature
- Analyse this research
- Provide an objective report.

Key findings

The key finding from is project are:

1) The compromising of the ability of a track system to perform its function by various contaminants is a complex interaction involving many considerations
2) Considerable research exists on this and related subjects
3) The ability to leverage of this research is limited due to the site specific and contextual nature of the problem
4) An alternative is to use a number of control sites and GPR technology under a well-considered program to obtain empirical data; the results from this study may have limited application retrospectively given the progressive implementation of mitigation measures.

1 Background

1.1 Central Queensland Coal Network (CQCN)

Aurizon Network ('Aurizon') manages the below rail infrastructure of the Central Queensland Coal Network ('CQCN'). The CQCN is an element in the pit to port supply chain that enables the coal from the Bowen Basin to be transported to the export terminals at Bowen, Mackay and Gladstone. The other elements in this supply chain are the:

- mines, including loading facilities
- above rail, or rolling stock, operators
- terminals, including unloading facilities.

An issue for all stakeholders in the supply chain is the impact of coal spillage on the below rail asset. Contamination of the track system by coal particles leads to a significant reduction in the engineering performance of the track system. The predominant mechanism to remove this contamination is through expensive and time consuming ballast cleaning operations.

It is in the interest of all stakeholders to have an understanding of the nature of contamination that can lead to a compromised track system; and consequently work towards an achievable optimum strategy to address the issue.

1.2 Regulated Asset

The below rail asset is a declared facility under the Queensland Rail Access Regime; consequently it is regulated by the Queensland Competition Authority (the 'Authority'). Aurizon operates under an established system based on an access undertaking approved by the Authority which sets performance targets for Aurizon.

1.3 Operational Context

The issue of contamination of the track system by coal spillage, or other mechanisms, must be considered within the operational context of the CQCN. Some considerations to take into account are as listed in Table 1.

Table 1: Operational Considerations

Consideration	Comments
Climate	The CQCN is exposed to tropical seasonal variations with periods of high rainfall experienced annually between January-April.
Safety	The Aurizon Network operates under Rail Safety Act requirements and an internal ZERO Harm Policy that ensures a safe and healthy work environment.
Capital Planning	Assets identified and approaching replacement/renewal may be maintained to a lower degree; whilst maintaining acceptable contractual requirements.
Reactive Maintenance	Reactive spot maintenance on the asset is not always possible and must be co-ordinated with other associated works.
Possession Planning	Access to the below rail asset must be coordinated with above rail operations. This access is normally planned in detail well before the possession (or track access) occurs.

2 Brief

2.1 General

Evans & Peck's task was to scope the interrelationships that lead to a compromised track structure and make comment on the ability to isolate aspects related to coal spillage through various causes.

The study was to include the following considerations of coal spillage:

- the relevant proportion of sources of coal spillage
- the rate of coal spillage and contributing factors to those sources
- the evaluation of the effectiveness of the mitigating measures
- the availability and effectiveness of topper agents available since 2001
- the capital and operating costs of profiling and veneering stations
- the cost of implementing the relevant mitigation
- the lost coal sales volumes associated with implementation of mitigation measures
- the contribution of coal as a contaminant relevant to other sources of fouling
- the capacity losses associated with the relevant mitigation strategy
- the impact of actual train operations since 2001 on the infrastructure as constructed
- the capacity losses directly attributable to ballast cleaning activities
- a determination through both econometric and engineering based approaches the contribution coal spillage has towards speed restrictions
- the costs and supplementary processing requirements associated with a 3 inch coal processing size
- the methods of monitoring compliance with loading performance standards and operational disruptions attributable to issuance notice to remedy
- the costs of wagon washing facilities and waste disposal costs at each unload point and any resultant increased rollingstock maintenance requirements arising from corrosion and, or bearing contamination, and
- the normalised ballast undercutting requirements, and therefore the net savings to industry, associated with implementation of any mitigation.

2.2 Objective

The objective this report is to provide a general scoping study of the nature of track system contamination. The scoping study is to outline the nature of the interactions involved and identify what activities would be required to gain a greater understanding of specific aspects of historical and current track system contamination.

2.3 Qualification and Assumptions

This report is not comprehensive and does not aim to provide anything other than a general understanding of the dynamics and interactions that lead to a compromised track system.

As this was limited to a scoping study, no new research was undertaken by Evans & Peck.

It does summarise the results of a literature search on the subject of ballast fouling on heavy haul railway systems; however it should be noted that some research on this subject is not readily available, or available only in a redacted form.

3 Methodology

3.1 Overview

The assessment was undertaken in three stages as follows:

Table 2: Stages

Stage 1: Research	• Research of ballast fouling causes and their mechanisms and related case studies • Development of diagrams showing identified causes of ballast fouling and their interrelationships.
Stage 2: Analysis	• Analysis and presentation of findings to Aurizon.
Stage 3: Report	• Preparation of a final report.

3.2 Stage 1: Research

The research focused on the nature and causes of ballast fouling. Specific coverage included:

- ballast maintenance principles
- sources of contaminants, and
- the nature of ballast contamination.

3.3 Stage 2: Analysis

The research work identified in Stage 1 was reviewed in terms of objectives, scope and findings.

This review was conducted based on a framework of the considerations identified by Aurizon, as listed in Section 2.1.

On the completion of the analysis; a briefing was provided to Aurizon. This briefing was used to obtain direction in regard to final research activities and preparation of the final report.

3.4 Stage 3: Report

The results of the scoping study were then documented into this final report.

4 Findings

Evans & Peck's scoping study identified findings in regard to each of the considerations. In general the findings support a view that the compromising of a track system by contaminants is context specific and is a complex subject with many dynamic contributing factors. The findings are listed in Table 3 below.

Table 3: Findings

Item No.	Description	Finding
1	Relative proportion of sources of coal spillage.	In order to determine the relevant proportion of sources of coal spillage data would be required through a combination of field measurements and computerised models such as the Computerised Particle Dynamic (CPD) models. Developments in Ground Penetrating Radar (GPR) technology may provide an opportunity to derive an understanding of the relative proportion of the sources of coal spillage by the use of a number of carefully chosen control sites.
2	Rate of coal spillage and contributing factors to those sources, including environmental factors.	This research would involve similar studies to those required for Item 1. As above, developments in GPR technology and analysis may provide an opportunity to derive an understanding of the rate of coal spillage by the use of a number of control sites. These sites would need to be selected to evaluate spillage rates with and without mitigation measures which may be undesirable from the environmental perspective.
3	Evaluation of the effectiveness of the mitigation measures including impact on fouling rates.	This would require a similar set of studies as those required above in Items 1 and 2.
4	Availability and effectiveness of topper agents available since 2001.	A study of these would require a combination of engaging with topper agent suppliers and possibly some field trials.
5	Capital and operating costs of veneering stations, including mine water supply costs and integration into lead-out.	Reasonable estimates could be achieved through a detailed cost estimating exercise.
6	Cost of implementing the relevant mitigation, including both capital and operating costs.	This would require a dynamic model that could provide insight into the effectiveness of the coal supply chain with mitigation measures as opposed to the operation of the supply chain without these measures. It is advisable also to calibrate such a dynamic model against actual results.
7	Lost coal sales volumes associated with implementation of mitigation measures and investment lead times.	This analysis would require a relatively sophisticated economic model based on a series of assumptions.

Item No.	Description	Finding
8	Contribution of coal as a contaminant relative to other sources of fouling.	The interrelationship of factors that can compromise the capacity of a track system is complicated and dynamic. It is quite difficult to isolate the specific contribution of any single element. This analysis would require a model, rely on a number of assumptions, be susceptible to context specific factors and require calibration.
9	Capacity losses associated with the relevant mitigation strategy and the additional track and rolling stock and the infrastructure required to offset volumetric constraints.	This analysis would require a relatively sophisticated economic model.
10	Impact of prevailing train operations since 2001 on the infrastructure standard and condition relevant to the original asset valuation.	To achieve an understanding of the impact of prevailing train operations since 2001 a base line condition for 2001 would have to be assumed for each of the four systems and a simplification of the coal spillage impact interrelationship would have to be derived and applied. The accuracy of such an analysis would require some degree of calibration.
11	Capacity losses directly attributable to ballast cleaning activities.	An understanding of capacity losses due to ballast cleaning operations could be achieved through an analysis that: • assessed the ballast cleaning requirement without mitigation measures • assessed the ballast cleaning requirement with mitigation measures • allowed for ballast cleaning required for other contamination • allowing for ballast cleaning conducted during agreed non-productive periods of mines and ports.
12	Costs and supplementary processing requirements associated with a 3 inch coal processing size.	Reasonable estimates could be achieved through a detailed cost estimating exercise.
13	Methods of monitoring compliance with loading performance standards and operational disruptions attributable to issuance notice to remedy.	A system to monitor and enforce compliance would have to be carefully structured to achieve stakeholder commitment and balance effectiveness with effort. Once a system is agreed by stakeholders then reasonable estimates could be achieved through a detailed cost estimating exercise.
14	The costs of wagon washing facilities and waste disposal costs at each unload point.	Reasonable estimates could be achieved through a detailed cost estimating exercise.
15	Increased rolling stock maintenance requirements arising from corrosion and, or bearing contamination.	An analysis of this would require a number of assumptions to be made and an economic model to determine a range of potential impacts.
16	The normalised ballast undercutting requirements, and therefore the net savings to industry, associated with implementation of any relevant mitigation.	This aspect is related to Item 11 and would essentially be the same modelling exercise. Dependence on assumptions and difficulty in calibration would complicate such an analysis.

5 Analysis

5.1 General

Analysis was conducted into the level and nature of research conducted into the following considerations of coal spillage:

- the relevant proportion of sources of coal spillage
- the rate of coal spillage and contributing factors to those sources
- the evaluation of the effectiveness of the mitigating measures
- the availability and effectiveness of topper agents available since 2001
- the capital and operating costs of profiling and veneering stations
- the cost of implementing the relevant mitigation
- the lost coal sales volumes associated with implementation of mitigation measures
- the contribution of coal as a contaminant relevant to other sources of fouling;
- the capacity losses associated with the relevant mitigation strategy
- the impact of actual train operations since 2001 on the infrastructure as constructed
- the capacity losses directly attributable to ballast cleaning activities
- a determination through both econometric and engineering based approaches the contribution coal spillage has towards speed restrictions
- the costs and supplementary processing requirements associated with a 3 inch coal processing size
- the methods of monitoring compliance with loading performance standards and operational disruptions attributable to issuance notice to remedy
- the costs of wagon washing facilities and waste disposal costs at each unload point and any resultant increased rollingstock maintenance requirements arising from corrosion and, or bearing contamination, and
- the normalised ballast undercutting requirements, and therefore the net savings to industry, associated with implementation of any mitigation.

5.2 Coal Spillage Considerations

5.2.1 Relative Proportion of Sources

Evans & Peck conducted a literature search to gauge the current level of research into the subject of sources of coal spillage. The results of this search are included at Appendix A.

In 1994, Selig and Waters[1] categorised the sources of ballast fouling into five groups:

- ballast breakdown
- sleeper wear

[1] E. T. Selig and J. M. Waters, Track Geotechnology and Substructure Management, New York, NY: Thomas Telford, 1994.

- infiltration from ballast surface
- subgrade infiltration and infiltration
- from underlying granular layer.

Ballast breakdown can occur during transportation and handling or over time due to chemical interactions. Selig and Waters concluded that this can account for over three quarters of ballast fouling.

In 2002, Feldman and Nissen[2] reported that for tracks in Australia used predominantly for coal transport, coal dust accounted for 70-95% of contaminants and ballast breakdown contributes from 5-30%.

Evans & Peck have utilised the information out of these various studies to derive a diagram of the interactions that cause ballast contamination.

Figure 1 shows this interaction in a way that illustrates the dynamic and interrelated nature of the various elements.

Figure 2 shows this interrelationship in an alternative cause and event type layout. Evans & Peck suggest the interrelationship is more accurately portrayed in Figure 1; as this shows the interactive nature of the causes and effects as opposed to a simplistic linear relationship.

Huang, Tutumluer and Dombrow[3] conducted a detailed study on the effect of different fouling agents as a part of the laboratory program initiated by the University of Illinois. The change in shear strength with increasing weight percentage of different fouling agent was observed in this study. The results showed that coal dust was the worst fouling agent among other fine particles tested and drastically decreased shear strength. The ballast reached the critical level of contamination at 15% by weight and the strength decreased to the equivalent level as coal dust itself at 35% by weight. However, the researchers also discussed on the limitations of the results obtained due to the differences between laboratory and field conditions.

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[2] F. Feldman and D. Nissen, "Alternative Testing Method for the Measurement of Ballast Fouling: Percentage Void Contamination," in *Conference on Railway Engineering*, Wollongong, 2002.

[3] H. Huang, E. Tutumluer and W. Dombrow, "Laboratory Characterisation of Fouled Railroad Ballast Behaviour," *Journal of the Transportation Research Board*, no. 2117, pp. 93-101, 2009.

Figure 1: Ballast fouling interrelationships

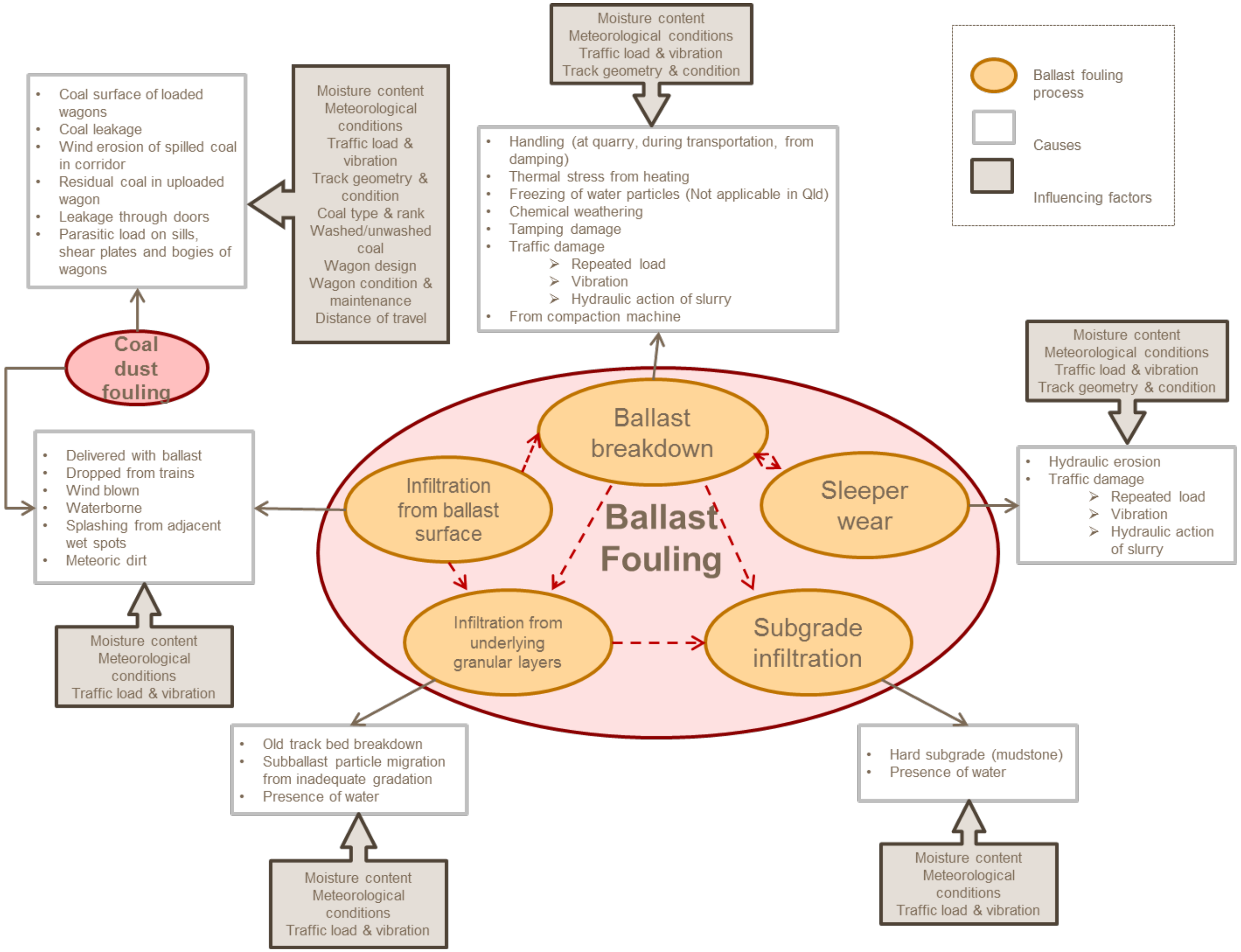
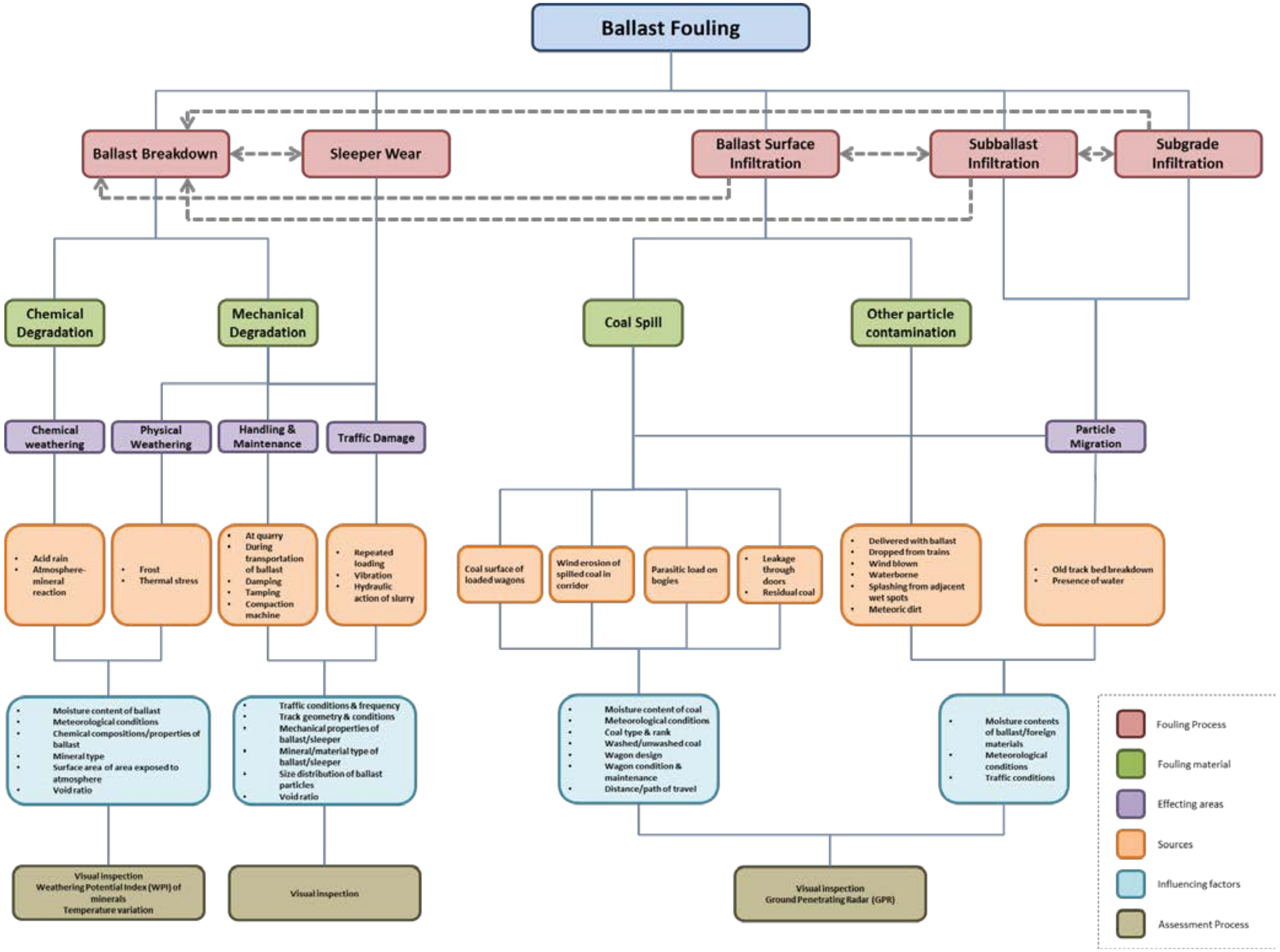


Figure 2: Ballast fouling interrelationships (Cause and Event layout)



Coal spillage from wagons can be from:

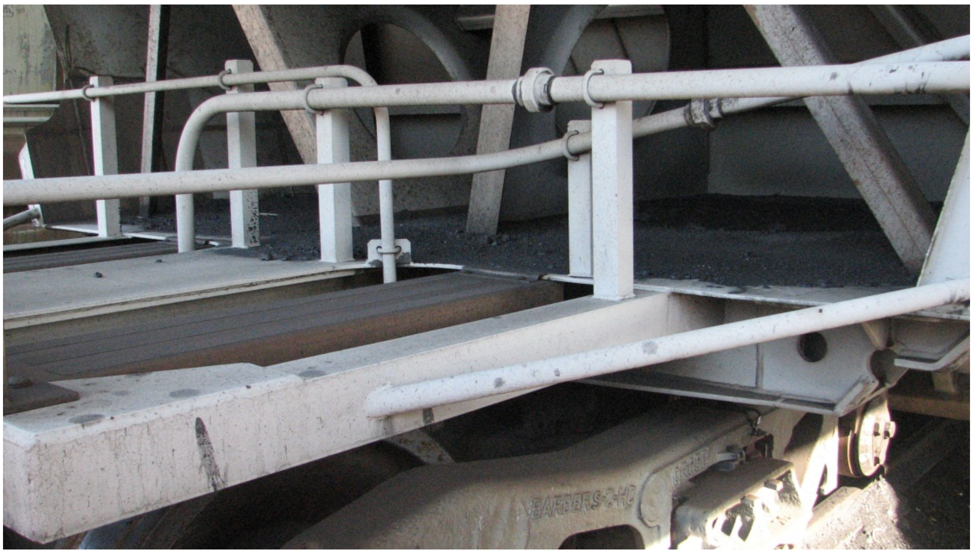
- Parasitic coal on external parts of the wagon due to poor loading practice
- Coal erosion and spillage from the top of the wagon
- Coal falling through the doors
- Coal ploughed from loading or unloading facilities.

In order to determine the relevant proportion of sources of coal spillage data through a combination of field measurements and computerised models such as the Computerised Particle Dynamic ('CPD') models run by CSIRO would be required.

Examples of parasitic coal on rolling stock are shown on Figures 3 and 4 below.

Figure 3: Example of parasitic coal on a wheel bogie

Figure 4: Example of parasitic coal on a wagon



Carry back occurs when a wagon does not fully empty at an unloader station at a terminal. According to the survey conducted in 2007[4], an average coal wagon was determined to have carry-back of approximately 0.36 tonnes; however the figure increased to 0.93 tonnes after torrential rains during the survey period.

It is questionable whether specific context specific studies or models could be applied generically across arrange of systems; therefore analyses would have to be conducted based on a range of scenarios.

Developments in Ground Penetrating Radar ('GPR') technology and analysis may provide the opportunity to derive an understanding of the relative proportion of sources of coal spillage by the use of a number of carefully sited control sites.

5.2.2 Rate Spillage

Currently this data is not widely available. Aurizon will potentially hold wagon weight data from the mine as a starting point. Some studies have been completed into specific aspects of the rate of spillage; such as Aurecon Hatch's analysis into leakage through Kwik Drop Doors.[5]

As above, developments in GPR technology and analysis may provide the opportunity to derive an understanding of the relative proportion of sources of coal spillage by the use of a number of carefully sited control sites.

5.2.3 Effectiveness of Mitigation Measures

This would require a similar set of studies as those required above for sections 5.2.1 and 5.2.2.

In addition these studies would have to be conducted at a number of points in time to confirm effectiveness.

5.2.4 Effectiveness of Topper Agents

There is existing data from suppliers on performance of current topper agents. However a context specific study for wind-blown coal spillage would require a combination of engaging with topper agent suppliers and possibly some field trials. Obtaining product samples for the period of 2001-2006 may not be feasible, limiting the study on historical performance to studies performed on the practical application of topper agents for similar loading and operational forces.

5.2.5 Cost of Veneering and Profiling

This is potentially commercially sensitive information. It is also context specific depending on water use within a particular mine subject to how the mine operation collects (water, harvesting, dams etc.). Notwithstanding this reasonable estimates could be achieved through a detailed cost estimating exercise.

5.2.6 Cost of Implementation of Mitigation Measures

This exercise is more complex that the exercise required for Finding 5. This would require construction of a dynamic model that could provide insight into the effectiveness of the coal supply

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[4] Hargrave, Chad; Haustein, Kerstin; Thompson, Jeremy; Einicke, Garry; Plunkett, Clive; Paterson, Syd;, "Final Report - Reduction of Carry-back and Coal Spillage in Rail Transport," CSIRO, Queensland, Australia, 2008.

[5] "Coal Leakage from Kwik Drop Doors", Aurecon Hatch, Queensland, Australia, 2009.

chain with mitigation measures as opposed to the operation of the supply chain without mitigation measures.

It is advisable also to calibrate such a dynamic model against some actual results.

5.2.7 Lost Coal Sales due to Mitigation Measures

This analysis would require a relatively sophisticated economic model based on a series of assumptions; as stated in Section 5.2.5; it is advisable to calibrate such a model.

5.2.8 Contribution of Coal as a Contaminant

As Figure 1 illustrates the interrelationship of factors that can compromise the capacity of a track system is complicated and dynamic. It is quite difficult to isolate the specific contribution of any single element. In addition, such an analysis would have to look at ranging the contribution as a number of context specific aspects would impact an individual site; including:

- age
- initial engineering standards applied
- climate
- hydrology
- topography
- geotechnical factors
- traffic.

Figure 5 below illustrates the contextual nature of the ability to maintain the track system; in this situation the physical constraint of the fence line limits the effectiveness of mechanised ballast cleaning. Either side of this location is evidence of mechanised ballast cleaning. Similar situations that limit the application of mechanised ballast cleaning exist at the approach to bridges, in yards and at turnouts.

Figure 5: Ballast contaminated with coal spillage

This analysis would require a sophisticated model, rely on a number of assumptions, be susceptible to context specific factors and require field proofing or calibration.

5.2.9 Capacity Losses

This analysis would require an economic model. It would tend to be context specific and would provide a ranged result based on a number of assumptions in key areas; such as the loading profile under a non-mitigated scenario.

Irrespective of the complexity of the model and the resulting ranging the end result is likely to be a requirement for an increase in rolling stock and the consequent flow on effect to infrastructure and support assets. There would likely be a consequent effect on efficiency and margins across the supply chain.

5.2.10 Impact of Operations since 2001

In addition to be able to quantify the impact of a particular factor on the asset, two things are required:

- a starting base line of the asset codition
- an ability to isolate the impact of that particular factor.

In the case of the contamination of a track system with coal spillage in the CQCN this is problematic as the there is no base line of the asset condition as it was in 2001 and as described earlier in this document the coal spillage interrelationship is complicated.

The development of the individual systems within the CQCN has varied. Some systems such as Moura and Newlands are older and were constructed to less rigorous engineering standards than the newer systems. The capacities of the systems in terms of axle load and train length have varied over time.

In order to achieve an understanding of the impact of prevailing train operations since 2001 a base line condition for 2001 would have to be assumed for each of the four systems and a simplification of the coal spillage impact interrelationship would have to be derived and applied. The accuracy of such an analysis would be questionable without some degree of calibration; it is difficult to see how this could be achieved.

5.2.11 Capacity Losses due to Ballast Cleaning

An understanding of capacity losses due to ballast cleaning operations could be achieved through an analysis that:

- assessed the ballast cleaning requirement without mitigation measures
- assessed the ballast cleaning requirement with mitigation measures
- allowed for ballast cleaning required for other contamination
- allowed for ballast cleaning conducted during agreed non-productive periods of mines and ports.

The first two items would require some assumptions but is achievable. These assumptions are complicated by the nature of the scheduling of ballast cleaning operations in the past. The scheduling of these operations did not have the benefit of technology such as GPR; consequently a combination of the location of Temporary Speed Restrictions, field testing and site inspections would be used to schedule ballast cleaning. The end result is that ballast cleaning has not been scheduled historically on an accurate measure of coal spillage contamination; simply because such technology was not available and also because other contextual factors contribute. A site that has been impacted by location specific formation design and construction factors as well as coal spillage contamination will also require ballast cleaning.

The other consideration in this assessment is that ballast cleaning operations have been generally scheduled to be completed during agreed non-operational periods. This complicates the assessment of whether a reduction on ballast cleaning operations would lead to an eventual increase in tonnage through better track capacity.

5.2.12 Costs Associated with Coal Processing Size

This is potentially commercially sensitive information. It is also context specific depending on the characteristics of coals at a particular mine. Costs such as additional crushing at source would have to be allowed for as well.

Notwithstanding this; reasonable estimates could be achieved through a detailed cost estimating exercise.

5.2.13 Methods of Monitoring Compliance

This aspect has a number of dimensions to it, including:

- agreement with all stakeholders on an effective monitoring and enforcement system
- the cost of monitoring and enforcement
- effective implementation of the monitoring compliance and enforcement system.

A system to monitor and enforce compliance would have to be carefully structured to achieve stakeholder commitment and balance effectiveness with effort.

Once a system is agreed by stakeholders then reasonable estimates could be achieved through a detailed cost estimating exercise. In the absence of an agreed system assumptions could be made that would allow the system to be estimated.

5.2.14 Costs of Wagon Washing Facilities

This is potentially commercially sensitive information. Notwithstanding this, reasonable estimates could be achieved through a detailed cost estimating exercise.

5.2.15 Impact on Rolling Stock Maintenance

The use of high pressure water can potentially have a detrimental effect on the mechanics of rolling stock. This may have the impact of increasing maintenance requirements of rolling stock, which in turn leads to flow on effects in terms of rolling stock and support facilities required. An analysis of this would require a number of assumptions to be made and an economic model to determine a range of potential impacts.

5.2.16 Normalised Ballast Undercutting Requirements

This aspect is related to Section 5.2.10 and would essentially be the same modelling exercise. It follows that with more control of the various causes of ballast contamination at the point of origin and the point of unloading that there would be a lesser requirement for ballast cleaning and potentially an increase in tonnage transported. The complication in this regard is the current ballast cleaning activities are scheduled to minimise impact on above rail operations; therefore the impact may not necessarily be proportionate.

This analysis would require a calibrated economic model with the ability to run a number of scenarios. Dependence on assumptions and difficulty in calibration would weaken the validity of the results of such analysis.

6 Disclaimer

This report has been prepared in accordance with the Agreement for Consultancy Services between Evans & Peck Pty Ltd and Aurizon Pty Ltd dated on or about 21 March 2013. Evans & Peck accepts no liability or responsibility whatsoever in respect of any use of, or reliance upon, this report by any other organisation or person.

Appendix A

Literature Review

No.	Year	Name	Objectives	Commissioned by	Completed by	Conclusions
1	1977	In-Transit Control of Coal Dust from Unit Trains	Investigation of effectiveness of chemical binders in controlling coal dust emanating from unit trains (study includes parameters such as loading profiles, chemical types, spraying technique etc.).	Environmental Protection Service – Fisheries and Environment (Canada)	C. Guarnaschelli	• Various chemical topper agents were tested • Oil spray and emulsions were the most effective products used to control dust because of their regenerative properties retaining cohesive cover over the coal surface.
2	1989	Evaluation of the Ability of Geotextiles to Prevent Pumping of Fines into Ballast (Master of Science Project)	Performance of geotextiles in preventing migration of fines under laboratory cyclic testing condition.	University of Massachusetts	B.J. Byrne	• Geotextiles were mostly suitable when used to prevent pumping of a fine soil that is broadly graded and contains significant amounts of sand-size particles • The use of geotextiles reduced the migration of fine-grained material into the upper ballast layer; however, they were not able to prevent pumping of soils consisting only of clay-size particles.
3	1991	Sources and Causes of Ballast Fouling		American Railway Engineering Association	E.T. Selig V. DelloRusso	
4	1994	Track Geotechnology and Substructure Management - Chapter 8: Ballast Maintenance Cycle Characteristics	Sources of ballast fouling and literature review and case studies of fouling mechanisms.		J. Waters E. Selig	• When the degree of fouling with fines is high enough, the fines will control the ballast behaviour and satisfactory geometry control will be impossible • Tamping becomes less effective as the degree of fouling increases • Ensure clean ballast is placed when new ballast is being installed • Minimise wagon spillage • Minimise tamping to decrease ballast damage caused by tamper tines.

No.	Year	Name	Objectives	Commissioned by	Completed by	Conclusions
5	1999	Imaging Attributes of Railway Track Formation and Ballast Using Ground Probing Radar	Use of GPR for assessing fouled ballast.	Scott Wilson Pavement Engineering GWR GTRM Amey Railways	R. Jack P. Jackson	• 450 and 900 MHz antennas of GPR was used for ballast NDT • At sites where the ballast is relatively clean the interface between ballast and subgrade has been clearly imaged • Changes in the quality of the image correlated with marked changes observed in trial pits • Significant improvements in track geometry records • Promising potential to improve economics of track maintenance Velocity field of electromagnetic radiation in the ballast and substructure is needed for accurate analysis and conversion of data (time required for radar reflection to depth profile) • Constant velocity can be used for data imaging • However, velocity varies with level of fouling, moisture contents (velocity is typically slower for dirty ballast).
6	1999	Application of ground-penetrating radar to railway track substructure maintenance management (Doctoral Thesis)	Investigation of the effects of GPR technique on different track structures with various conditions (moisture content etc.).	University of Massachusetts Amherst	T.R. Sussmann	• The analysis included comparison of the GPR data to track geometry, subsurface stratigraphy, and ballast condition (fouling and moisture). GPR processing techniques were developed to simplify interpretation of the data • The results showed that GPR could locate zones of increased substructure degradation at over 75% of the sites • Variations in dielectric constants due to different moisture contents of test samples can greatly influence the extent of the effects.
7	1999	Dynamic Response of Railroad Track Induced by High Speed Trains and Vertical Stiffness Transitions with Proposed Method of Measurements	Analysis of track response under high speed rail.	The University of Medford	G.A. Carr	• Limited application to heavy haul coal systems.

No.	Year	Name	Objectives	Commissioned by	Completed by	Conclusions
8	2002	Alternative Testing Method for the Measurement of Ballast Fouling: Percentage Void Contamination	Review alternative ballast fouling testing methods.	*Conference on Railway Engineering*, Wollongong	F. Feldman and D. Nissen	• Alternative method described.
9	2004	Development and Implementation for a Continuous Vertical Track-Support Testing Technique	Development and implementation of track loading vehicle technique to measure vertical track deflections under given vertical loads while in motion TLV is based on the ability to measure variations in vertical track deflection Technique was developed to identify weak locations and to determine load-carrying capacity of the track.	Association of American Railroads	D. Li R. Thompson P. Marquez S. Kalay	• The technique is capable of measuring vertical track support at a test speed of approx. 16km.h in both tangent and curved track • Can be used to locate the source of lower strength due to ballast and subgrade conditions and to assess the need for upgrades to accommodate higher operation speeds or loads.
10	2005	Mechanics of Ballasted Rail Tracks: A Geotechnical Perspective	Description of geotechnical aspects of track systems	N/A	B. Indraratna W. Salim	• Ballast breakage index to track severity of ballast breakdown.

No.	Year	Name	Objectives	Commissioned by	Completed by	Conclusions
11	2005	Degradation and Frost Susceptibility of Crushed Rock Aggregates Used in Structural Layers of Railway Track (Doctoral Thesis)	Analysis of factors affecting the degradation process of ballast Determination of properties of fines contained by ballast those accumulating in them in an actual ballast bed environment.	Tempereen University of Technology (Finland)	A. Nurmukolu	• Large proportions of ballast fouling is due to ballast breakdown • Chemical weathering of ballast samples proved to be insignificantly small and its effect is relatively localised to the surfaces of grains.
12	2008	Final Report - Reduction of Carry-back and Coal Spillage in Rail Transport	Field measurements of coal carry back.	CSIRO	Hargrave, Chad; Haustein, Kerstin; Thompson, Jeremy; Einicke, Garry; Plunkett, Clive; Paterson, Syd	• Coal carry back characteristics described.
13	2009	Laboratory Characterisation of Fouled Railroad Ballast Behaviour	Laboratory study of the effects of different fouling agents including coal dust, plastic clayey soil and mineral filler.	University of Illinois	H. Huang E. Tutumluer W. Dombrow	• As the coal dust fouling percentage increased, the ballast shear strength steadily decreased • Wet fouling was found to exacerbate this trend • Other fouling materials also showed the similar results but coal dust was determined to be the worst fouling agent • 15 weight % coal dust fouling was found to cause significant strength reduction of ballast • Once % reaches 35%, the friction angles of the aggregates decreased to almost as low as coal dust itself.
14	2009	Coal Leakage from Kwik Drop Doors	Field measurements of coal leakage through Kwik drop doors.	QR	Aurecon Hatch	• Coal leakage through doors quantified.

No.	Year	Name	Objectives	Commissioned by	Completed by	Conclusions
15	2010	Railroad Ballast Evaluation Using Ground-Penetrating Radar	Investigate the approaches used to overcome the limitations of GPR uses in ballast evaluation Measure dielectric constants and build STFT spectra for ballast under various fouling and moisture conditions.	Illinois Centre for Transpiration University of Illinois	Z. Leng I.L. Al-Qadi	• Moisture can significantly increase dielectric constant - positive linear relationship found • Detecting ballast fouling by the STFT (short time Fourier) method is based on the assumption that the GPR data collected is clean and without significant noise. However, during field data collection, many sources of noise (e.g., rails, ties, and radio signals) are generated, and this noise may mask the ballast information in the GPR data • STFT map can effectively detect locations of fouling and water accumulation if accurate dielectric constant is used – this result was validated by both laboratory and field data • Therefore further improvement of GPR data filtering and analysis are necessary • In order to maximise the outcome of GPR, appropriate guidelines must be developed by authorities.
16	2011	Implications of Ballast Breakage on Ballasted Railway Track Based on Numerical Modelling	Application of finite element analysis of elastoplastic deformation of ballast.	University of Wollongong	B. Indranatna S. Nimbalkar	• Theoretical model proposed.
17	2012	Mechanical Characterisation of Railway Structures Based on Vertical Stiffness Analysis and Railway Substructure Stress State	Stiffness analysis applied to railway structures.	*Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, vol. F, no. 227, pp. 74-85,	L. Montalban, J. Real and T. Real	• Theoretical model proposed.

No.	Year	Name	Objectives	Commissioned by	Completed by	Conclusions
18	2012	Source of Ballast Fouling and Influence Considerations for Condition Assessment Criteria	Discussion on the processes involved in ballast performance and failure Identification of the critical stages and methods for assessment.	U.S. Department of Transportation	T.R. Sussmann M. Ruel S.M. Charmer	• Coal dust can further exacerbate problems of reducing particle interlocking etc. as a result of even weaker structural response and the low specific gravity could lead to misleading estimates of the amount of fouling in the ballast • Application of track deflection or GPR appears to be the most direct and available means to assess ballast condition and provide a continuous evaluation of thresholds • More precise evaluation of ballast condition is essential to identify thresholds related to unsafe track support conditions and to support effective maintenance plans.

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