

Highway Filter Drains Maintenance Management

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HIGHWAY FILTER DRAINS MAINTENANCE MANAGEMENT

By
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A dissertation thesis submitted in partial fulfilment of the requirements for the award of the degree Doctor of Engineering (EngD), at Loughborough University

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ABSTRACT

Across a large part of the UK highways network the carriageway and pavement foundations are drained by Highway Filter Drains (HFDs). A HFD is a linear trench constructed either at the pavement edge or central reserve, fitted with a porous carrier pipe at the base and backfilled with an initially highly porous aggregate material. This arrangement enables the swift removal of surface runoff and subsurface water from the pavement system minimising road user hazards and eliminating risk of structural damage to the pavement sub-base. The highly porous backfill filters throughout its operational life fines washed from the pavement wearing course or adjacent land. HFDs have been found to be prone to collecting near the basal sections (pipe) or surface layers contaminants or detritus that causes the filter media to gradually block. The process has been defined as HFD clogging and it has been found to lead to reduced drainage capacity and potentially severe drop of serviceability.

O&M contractual agreements for DBFO projects usually propose in-service and handback requirements for all assets included in the concession portfolio. Different performance thresholds are thus prescribed for pavements, structures, ancillary assets or street lighting. Similar definitions can be retrieved for drainage assets in such agreements, and these include HFDs. Performance metrics are defined though in a generic language and residual life (a key indicator for major assets that usually drives long-term maintenance planning) is prescribed without indicative means to evaluate such a parameter.

Most of pavement maintenance is carried out nowadays using proactive management thinking and engineered assessment of benefits and costs of alternative strategies (what-if scenarios). Such a proactive regime is founded upon data driven processes and asset specific ageing / renewal understanding. Within the spectrum of road management, maintenance Life Cycle Costs are usually generated and updated on an annual basis using inventory and condition

data linked to a Decision Support Tool (DST). This enables the assessment and optimisation of investment requirements and projection of deterioration and of treatment impacts aligned to continuous monitoring of asset performance. Following this paradigm shift in infrastructure management, a similar structured methodology to optimise HFD maintenance planning is desired and is introduced in this thesis.

The work presented enables the identification of proactive maintenance drivers and potential routes in applying a systemised HFD appraisal and monitoring system. An evaluation of Asset Management prerequisites is thus discussed linked to an overview of strategic requirements to establish such a proactive approach. The thesis identifies condition assessment protocols and focuses on developing the means to evaluate deteriorated characteristics of in service drains using destructive and non-destructive techniques.

A probabilistic HFD ageing / renewal model is also proposed using Markov chains. This builds upon existing deterioration understanding and links back to current treatment options and impacts. A filter drain decision support toolkit is lastly developed to support maintenance planning and strategy generation.

KEY WORDS

Asset Management, Highway Filter Drains, Ground Penetrating Radar, Deterioration Modelling, Condition Assessment.

PREFACE

The research work presented within this thesis was undertaken between 2012 and 2016 in partial fulfilment of the requirements of the Engineering Doctorate (EngD) at the Centre for Innovative and Collaborative Construction Engineering (CICE). The industrial focused research was jointly sponsored by Engineering and Physical Sciences Research Council (EPSRC) and Balfour Beatty through its subsidiary Connect Roads.

The doctorate is examined on the basis of a written thesis supported by a minimum of three academic publications (at least one being a journal publication). Four papers are attached here and can be found in Appendices A to D. The information provided in the main body of the thesis is supplemented by the peer-reviewed papers and it should hence be read in conjunction with them.

USED ACRONYMS / ABBREVIATIONS

AMS	Asset Management System
AM	Asset Management
BB	Balfour Beatty
CR	Connect Roads
DBFO	Design Build Finance and Operate (30 yr. PFI projects)
DST	Decision Support Tool
EngD	Engineering Doctorate
HFDs	Highway Filter Drain(s)
LOS	Levels of Service
MAC	Managing Agent Contractor
MM	Maintenance Management
MMS	Maintenance Management System
PMS	Pavement Management System
PM	Pavement Management
PFI	Private Finance Initiative
RE	Research Engineer
RL	Residual Life (measured in years)
SPV	Special Purpose Vehicle
TPM	Transition Probability Matrix (Markov Chain)

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LIST OF PAPERS

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PAPER 1 (SEE APPENDIX A)

STYLIANIDES, T., FROST, M., FLEMING, P., ELJABER, A. & MAGEEAN, M. Assessment of Highway Filter Drain Fouling and Performance Considerations. Transportation Research Board 94th Annual Meeting, 2015

PAPER 2 (SEE APPENDIX B)

Stylianides, T., Frost, M.W., Fleming, P.R., El-Jaber, A., Mageean, M., Huetson, A. and Klimczak, T., 2015. Highway filter drains: precursors for maintenance management. *Infrastructure Asset Management*, 2(4), pp.159-172.

PAPER 3 (SEE APPENDIX C)

STYLIANIDES, T., FROST, M., FLEMING, P., MAGEEAN, M. & HUETSON, A. 2016. A Condition Assessment Approach for Highway Filter Drains using GPR. *Procedia Engineering*, 143, 1-10

PAPER 4 (SEE APPENDIX D)

STYLIANIDES, T., FROST, M.W., FLEMING, P.R., MAGEEAN, M., 2016 Geophysical investigation of Highway Filter Drains; condition evaluation methodologies using Ground Penetrating Radar. *International Journal of Pavement Engineering – [in progress]*

1 BACKGROUND TO THE RESEARCH

This chapter defines the structure of the thesis and introduces all subsequent chapters presented. The subject domain, justification for work undertaken and all relevant project information are overviewed and explained.

1.1 THE SUBJECT DOMAIN

Across a large part of the UK highway network the road carriageways and pavement sub-surface are drained by highway filter drains (HFDs). Filter drains are stone filled trenches, fitted with a porous carrier drain at the base to remove and convey pavement runoff and subsurface water to an outfall.

HFDs are prone to collecting, at or near the surface, any contamination, vegetation or detritus, which is washed or blown off the adjacent carriageway or earthwork slopes. Over time, this causes the filter media to block at the near surface or the material to be washed down into the drain further limiting the performance of the media or carrier drain. Such loss of performance can have detrimental effects on road safety by water ponding across the carriageway at an area of failed drainage, or on pavement life by water ingress into the road substructure.

Within the realm of highway infrastructure management, there has been in an ever increasing effort to introduce proactive maintenance thinking to pavement, structure and ancillary assets. Such an approach has lead over time to the formulation of engineered and objective condition evaluation and maintenance prioritisation systems that look to optimise the allocation of investments across various asset categories. A consistent approach to managing infrastructure is believed to produce a better understanding of investment needs and evaluation of alternative maintenance strategies.

The work carried out and summarised in this thesis revolves around the introduction of a maintenance management framework to support proactive decision making in respect to

intervention planning and HFD renewal policies. Throughout the report the terms Maintenance Management and Asset Management are interchangeable; both refer to a holistic system that integrates such elements as condition assessment, deterioration prediction, asset ageing and renewal rules and maintenance planning.

1.2 THE INDUSTRIAL SPONSORS

Connect Roads (CR) is a subsidiary of Balfour Beatty, that operates across the infrastructure lifecycle and is the largest company working within the UK highways sector, which includes the PFI market.

Balfour has four market-leading businesses in professional services, construction services, support services and infrastructure investments. Connect is one of the UK's largest private sector road operators which includes five concessions (A50, A30/A35, M1A1, CNDR, M77) and the M25 London Orbital, via its sister brand Connect Plus.

Connect Roads operates and maintains 360km of trunk road network; in partnership with its Term Maintenance subcontractors, CR undertakes all the operations and maintenance requirements for those routes using proprietary Decision Support Tools and proactive maintenance planning.

1.3 THE CONTEXT OF THE RESEARCH

Asset Management thinking has been central to highways operations for a few decades. It has evolved over the years to incorporate business principles and to align engineering thinking to a more strategic view of the nation's infrastructure. A number of definitions can be retrieved in available literature (academic or state of practise) that define what AM represents and how it is approached. In reality, most practitioners share similar views to how proactive

maintenance thinking should be deployed for key asset groups and various systems are defined and structured around asset-specific in-service and handback requirements.

Highway maintenance is now undertaken on a planned and preventative basis with asset owners and overseeing organisations employing condition and risk based decision support tools and deterioration and future investment requirements prediction routines. This is normally achieved by focusing on regular monitoring of the highway network and recording and upgrading inventory data, distress information and deterioration trends within inventory databases linked to pavement management systems. The reality though is that lacking a similar fundamental approach, drainage infrastructure seldom forms an integral part of these monitoring or management activities scoring lower as a priority in infrastructure management. There have been efforts to gradually roll out asset management thinking for the purpose of a more strategic approach to drainage management, but often these fail to approach the topic in a holistic manner that tackles the full AM cycle (understand your asset, evaluate condition, evaluate what-if scenarios and prioritise intervention).

There is currently no established management system available to monitor the performance and ageing of filter drains. With no apparent routine to systematically assess the asset's condition and deteriorated characteristics, maintenance is typically carried out under a reactive approach (find and fix). Alternatively, a time-based approach can be deployed on site but lacking accurate means to establish deterioration projection leads to under or overinvestment in most practical scenarios. Intervention options normally involve the excavation of the drains and their replacement with new material (dig and replace) or scarifying the top layers of the trench.

A number of DBFO concessions across CR's investment portfolio are steadily moving to their last operation stage, handback. Typical handback requirements prescribe asset specific performance and residual life thresholds to be met for each asset category across the

concession asset portfolio (structures, pavement, ancillary assets, road furniture). Pavement sections for example can be required to be defect-free, have a larger than 10 years residual-life, and remain below a 11mm rutting threshold. In a similar fashion such contractual requirements define a 5yr residual life for HFD. No further classification is offered to enable CR to evaluate the asset's RL current condition and physical deterioration. When a HFD proactive management system is in place, a supporting framework that facilitates condition evaluation and deterioration projection will run in parallel with existing Pavement Management Systems (PMS). This will allow for continuous monitoring and planned maintenance, essentially enabling the selection of the right treatment for the right asset at the right time - the motto integrated in pavement maintenance during the transition from reactive to proactive intervention philosophies.

1.4 AIM AND OBJECTIVES

1.4.1 PROJECT AIM

The aim off this project is to develop a maintenance evaluation and management system that will allow the development and adoption of proactive and optimised maintenance strategies for highway filter drains.

Individual objectives leading to the overarching aim are listed and briefly overviewed in the following sections.

1.4.2 OBJECTIVE ONE – INVESTIGATE CURRENT STATE OF ASSET

MANAGEMENT; DEFINE INFORMATION NEEDS TO ESTABLISH PROACTIVE HIGHWAY FILTER DRAIN MAINTENANCE APPROACHES

The first objective facilitates the requirement to develop an understanding of the strategic end of the AM equation upon which the maintenance management system will be developed. The sub-objectives defined by the RE and the industrial sponsor were:

- Review PMS state of the practise.
- Identify drivers for Drainage Asset Management.
- Identify information requirements pertaining to a HFD specific maintenance management system.

1.4.3 OBJECTIVE TWO - EVALUATE CURRENT STATE OF HFD DETERIORATION

UNDERSTANDING AND MAINTENANCE PRACTICE (RESEARCH SPONSOR AND WIDER HIGHWAYS SECTOR)

The second objective focused on understanding the in-service performance, deterioration characteristics and maintenance options of the drainage asset following and defining in a sense the current state of practice.

Sub-objectives were hence defined and listed below:

- Explore sponsor's approach to HFD MM.
- Investigate and compare deterioration information and service life projections (design manuals, site crew experience, wider industry).
- Carry out preliminary in-situ HFD assessment exercises

1.4.4 OBJECTIVE THREE – ASSESS THE APPLICATION OF HFD SPECIFIC CONDITION AND SERVICEABILITY ASSESSMENT ROUTINES

While condition evaluation forms an integral part of the MM being proposed, objective three was introduced as a stand-alone milestone with a number of associated work-packages because of the unique problem presented with the evaluation of in-service HFDs. A number of interlinked sub-objectives were thus generated targeting laboratory and field exercises in an attempt to define

- What can be used as a HFD condition descriptor
- How can that be extracted from in-service trenches
- How is it accountable for anticipated performance

1.4.5 OBJECTIVE FOUR – PROPOSE AN INTERNAL MAINTENANCE MANAGEMENT STANDARD TO SUPPORT PROACTIVE HFD MAINTENANCE FOR CR

Building upon the outputs of objectives one to three, the fourth objective (and respectively the work packages which support its completion) focused on proposing a MM standard to be adopted from the industrial sponsor. This targets the optimisation of assets maintenance and renewal operations approaching network level deterioration modelling through a semi-empirical / probabilistic route founded upon inventory and condition data, in-service requirements and investment prioritisation means.

1.4.6 JUSTIFICATION OF OBJECTIVES

The four objectives are structured in such a way as to follow generic AM / PM principles linked to the particular design, in service and handback requirements and characteristics of Highway Filter Drains. Standardised protocols (BSI standards, PAL-55) pertaining to the

management of tangible assets are readily available and these generally define how proactive management can be achieved. Such documents are though in a sense overarching strategic guides that define generic AM requirements and lack the engineering prerequisites that are unique for each asset category.

The use of Decision Support Tools that sit at the core of Bridge or Pavement Management Systems and drive long term decision making, require an in-depth engineering understanding of the evaluated asset type. This understanding is derived from continuous monitoring hence from the adaption of ‘proper’ monitoring methods, from modelling techniques thus mathematical representations of ageing / renewal rules, from treatment triggers and impacts thus evaluation of intervention optioneering and from evaluation of in-service and handback requirements, thus evaluation of serviceability.

Applying an AM-specific approach requires a thorough consideration of the uniqueness of each asset category embedded within the wider AM-framework. Adopting proactive thinking and investment optimisation requires transposing a fundamentally universal systemised approach (that is AM) to asset-specific requirements (be it pavement, drainage, bridge or street furniture). The four objectives communicate this requirement; the alignment of proactive management thinking at both the strategic and tactical levels to the specific characteristics of HFD is completed by evaluating the business and engineering sides of the AM equation and by addressing the particular Pavement Management approach adopted by the industrial sponsor.

Such an approach has not been thoroughly examined to date; HFD in-service and hand-back requirements are often prescribed in a generic language, asset inventories and lacking and condition assessment has not previously been addressed in a quantitative manner. The work thus addresses information needs to reach such a proactive approach and the means to achieve

a structured Maintenance Management system (inventory collection, condition assessment means, deterioration modelling options and ageing / renewal rules).

1.5 LIST OF PUBLICATIONS

Peer reviewed papers published to disseminate the findings of this research project are summarized in Table 1.

Table 1 List of Publications

Paper N ^o	Paper Title	Full Reference	Status
Paper 1 Appendix A	Assessment of Highway Filter Drain Fouling and Performance Considerations	STYLIANIDES, T., FROST, M., FLEMING, P., ELJABER, A. & MAGEEAN, M. Assessment of Highway Filter Drain Fouling and Performance Considerations. Transportation Research Board 94th Annual Meeting, 2015.	Published
Paper 2 Appendix B	Highway filter drains: precursors for maintenance management	Stylianides, Theodoros, Matthew W. Frost, Paul R. Fleming, Ali El-Jaber, Mark Mageean, Andrew Huetson, and Tomasz Klimczak. "Highway filter drains: precursors for maintenance management." <i>Infrastructure Asset Management 2, no. 4 (2015): 159-172.</i>	Published
Paper 3 Appendix C	A Condition Assessment Approach for Highway Filter Drains using GPR	STYLIANIDES, T., FROST, M., FLEMING, P., MAGEEAN, M. & HUETSON, A. 2016. A Condition Assessment Approach for Highway Filter Drains using GPR. <i>Procedia Engineering</i> , 143, 1-10	Published
Paper 4 – Appendix D	Geophysical investigation of Highway Filter Drains; condition evaluation methodologies using Ground Penetrating Radar	STYLIANIDES, T., FROST, M.W., FLEMING, P.R., MAGEEAN, M., 2016 Geophysical investigation of Highway Filter Drains; condition evaluation methodologies using Ground Penetrating Radar. <i>International Journal of Pavement Engineering – [in progress]</i>	In progress

1.6 STRUCTURE OF THESIS

The thesis is organised in five chapters.

Chapter 2 presents a detailed overview of current practise and related work related to HFD deterioration and maintenance understanding. It also introduces AM principles and components of a system that would enable proactive maintenance planning.

Chapter 3 presents the research methodology adopted to approach the research project aim. Work packages and research tasks formulated over the four years are described and outputs are explained.

Chapter 4 presents the research undertaken and results linked to all research tasks developed from Chapter 3. Inventory collection, condition assessment, maintenance prioritisation and DST setting up are explored and presented.

Chapter 5 outlines key findings from the research work and presents the work's impact on the wider industry, the academic community and the industrial sponsor. The chapter also presents a review of all the work done identifying potential routes for further work in the future.

1.7 SUMMARY

The chapter introduces the research work and breaks down research aim objectives and justification for all the work undertaken over the four-year period of the project. Chapter 2 then presents the detailed overview of literature and current state of practice.

2 CURRENT PRACTISE AND RELATED WORK

2.1 OVERVIEW

This chapter presents an overview of existing literature on Highway Filter Drains, their design, current deterioration and maintenance understanding. It also looks to establish the founding principles of proactive management thinking in the Highways sector; this identifies the gaps in existing HFD management literature and positions the research work within the wider body of IAMS. Principles related to Highway Asset Management are hence described and aims, objectives work-packages and routines developed for the completion of the work converge to the proactive maintenance thinking already employed for the management of other key assets.

2.2 LITERATURE REVIEW

2.2.1 HIGHWAY FILTER DRAINS

2.2.1.1 Design and applications

A generic definition of Highway Filter Drains is provided in HA 39/98 as ‘A *drain constructed using permeable materials which allows the entry of water whilst retaining the surrounding material*’. Filter drains are linear drainage systems consisting of a trench backfilled with large particle size aggregate material that generally offers high permeability capabilities. Originally, trenches were designed either with no carrier pipes or un-jointed pottery pipes at the bottom. In recent times, a few different carrier configurations have been adopted ranging from porous concrete, to PVC and fiberglass, embedding perforations to allow water collection. The conveyor at the base of the trench directs surface water runoff and subsurface water away from the pavement system to a watercourse. Typical carrier diameters

may vary between 150 and 275mm and they are laid adopting a longitudinal gradient (>0.25%) that enables self-cleaning conditions (Fáisca et al., 2009).

HFDs are longitudinal drainage systems; their main objective is to quickly and adequately collect rainwater from the pavement surface and immediate surroundings (edges, central reserve and slopes) and convey it safely away from the structure. The drains' trenches are constructed in verges and/or central reserves adjacent to low edges of pavements allowing surface water to run off the pavement (or surroundings) directly into the trench and permeate through the stone aggregate to the porous carrier pipe at the bottom. A geotextile is often used to prevent the entry of fines carried into the trench by either surface or sub-surface water ensuring the drain is kept clear to provide a free-draining path throughout its length. Geotextiles are also suggested as a 'design-to-maintain' approach in a number of manuals; their application may limit the ingress of sediments within an 'easy to manage' sacrificial top layer (Gloucester City Council, 2013) .

A number of inherent disadvantages and / or limitations have been reported in the past in regards to HFD operation. These principally are:

- Cost of suitably graded aggregate stone
- Need for regular maintenance to avoid vegetation build-up
- Stone scattering due to vehicular overrun
- Projected service life of 10 years hence expensive maintenance requirements over DBFO lifecycle projections (HA 39/38)

Despite the aforementioned limitations reported in recent years, the adoption of a HFD drainage systems is still described as the most cost effective available drainage option. Where large ground water flows from cuttings are to be dealt with or, where long and flat longitudinal gradients are designed, HFD can exhibit significant cost reductions. As a well-established technique, it is currently the cheapest and simplest type of drainage to construct.

HFD are reported to be a low embodied carbon solution and the option of using recycled materials adds to a positive sustainability contribution (Santhalingham, 2011).

General HFD design recommendations (applicable to the UK) for highway drainage systems can be found in the Design Manual for Road and Bridges (DMRB), Manual of Contract documents for Highway Works (MCHW) and the Trunk Road Maintenance Manual (TRMM). Good practice and general suggestions regarding application of filter drains can be traced across a wide spectrum of literature as filter drains (the terms French drains and infiltration trenches are used in different sectors) are applicable to drainage systems used in fields other than highways. In fact the stone aggregate backfilled trenches are often used in Sustainable Urban Drainage Systems (SUDS) and other general urban redevelopment schemes as they provide a sound and effective solution to storing rainwater runoff efficiently (Rao et al., 1991, Kellagher, 2004).

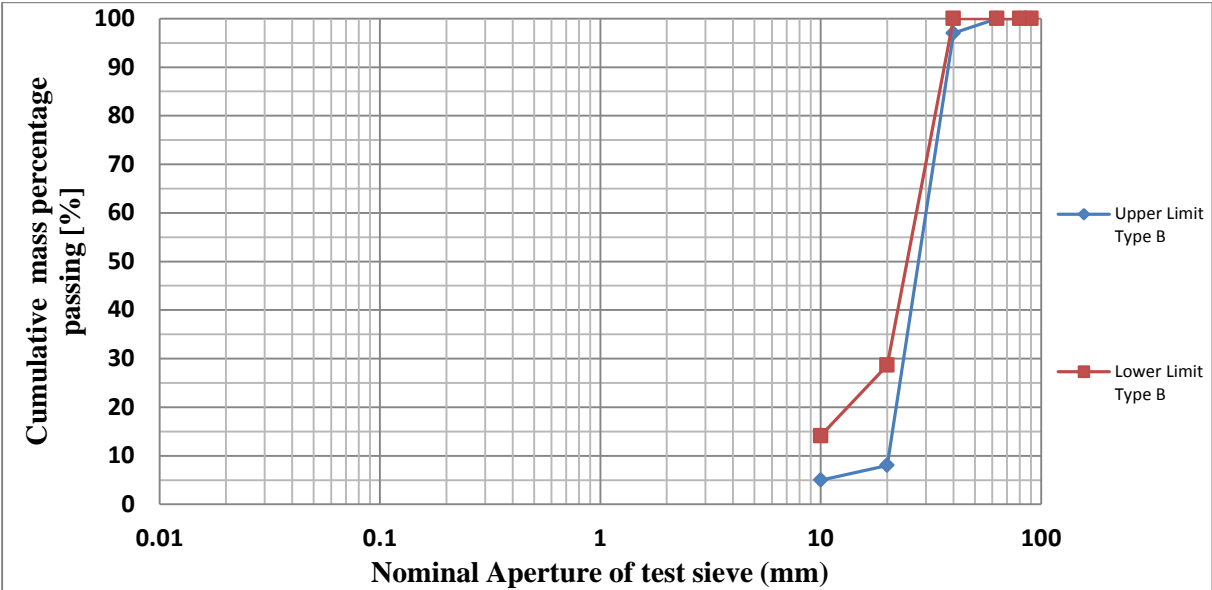


Figure 1 Grading Envelopes for Type B as found in DMRB, Series 500

The coarse gravel that forms the main drainage layer has at the beginning of its service life an extremely high porous nature and enables rapid removal of water. (2009) specifies two broad granular material gradings for aggregate used in the drains as Type A and B. Type A being a

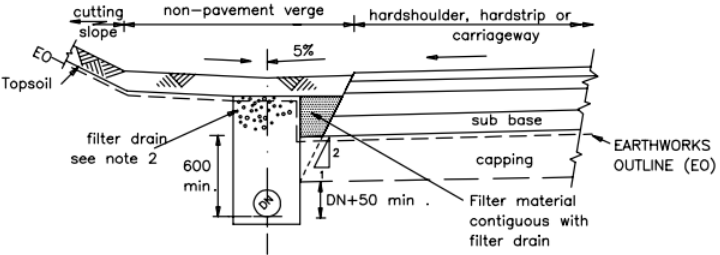
finer material. The former is selected as a balancing option between permeability and filtration of surface deposits, Type B (a coarser grading) offers higher permeability. The gradation envelope of Type B is visualised in Figure 1.

The minimum requirements for the infill are based on grading, water content and permeability. Type B material is the main type of stone currently used (at least in concessions managed by Balfour Beatty and reported case studies from around the UK network). In effect, the supply of aggregate type B stone varies as a function of the typical aggregate production in local quarries (it can be a by-product of different types of products or the actual product).

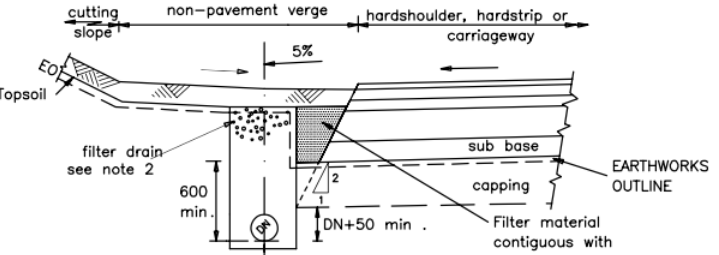
Extracts from the Design Manual for Roads and Bridges (B-series, F-series) that break down design options and different material configurations are shown in Figures 2 and 3. In (Samuel and Farrar, 1988a) four key points related to design and asset performance are described.

These are:

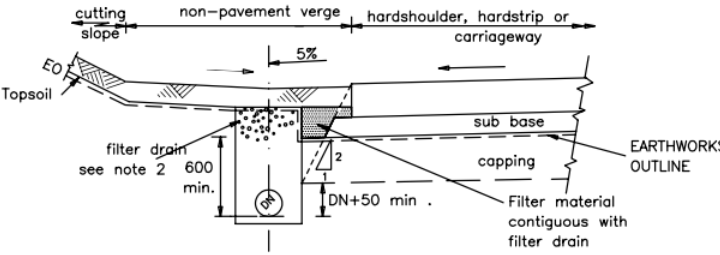
- **Specifications:** In general terms highway specifications allow the use of two main design options based on either Type A or Type B. Provision for alternative specifications (as a function of site conditions) is also provided (Type C) but that also factorises approval from overseeing organisation .
- **Construction:** HFDs perform effectively if and only if they are constructed according to specifications and damage / contamination during construction operations is limited.
- **Maintenance:** Efficient performance of assets in the short to medium term will be a function of extent of maintenance, vegetation control and ingress of detritus.
- **Long-term performance:** Performance over the projected service life can be affected by chemical or biological blockage or deterioration of filter material – no evidence of such events is considered a major issue in the UK.



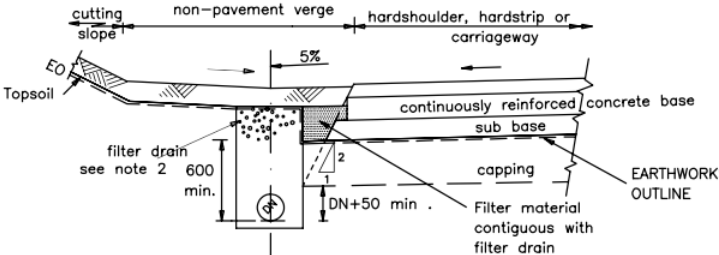
Type 1A (Flexible carriageway).



Type 1C (Flexible composite carriageway).



Type 1B (Rigid carriageway).



Type 1D (Rigid composite carriageway).

- NOTES
1. ALL DIMENSIONS ARE IN MILLIMETRES.
 2. Alternative treatments to top of filter drains are shown on Drawing No. B15. Type V is shown on this Drawing.
 3. 'DN' represents nominal diameter of the pipe.
 4. Pipes shall be laid to the levels shown on the Drawings and schedules.

Figure 2 Edge of pavement details (DMRB B-Series)

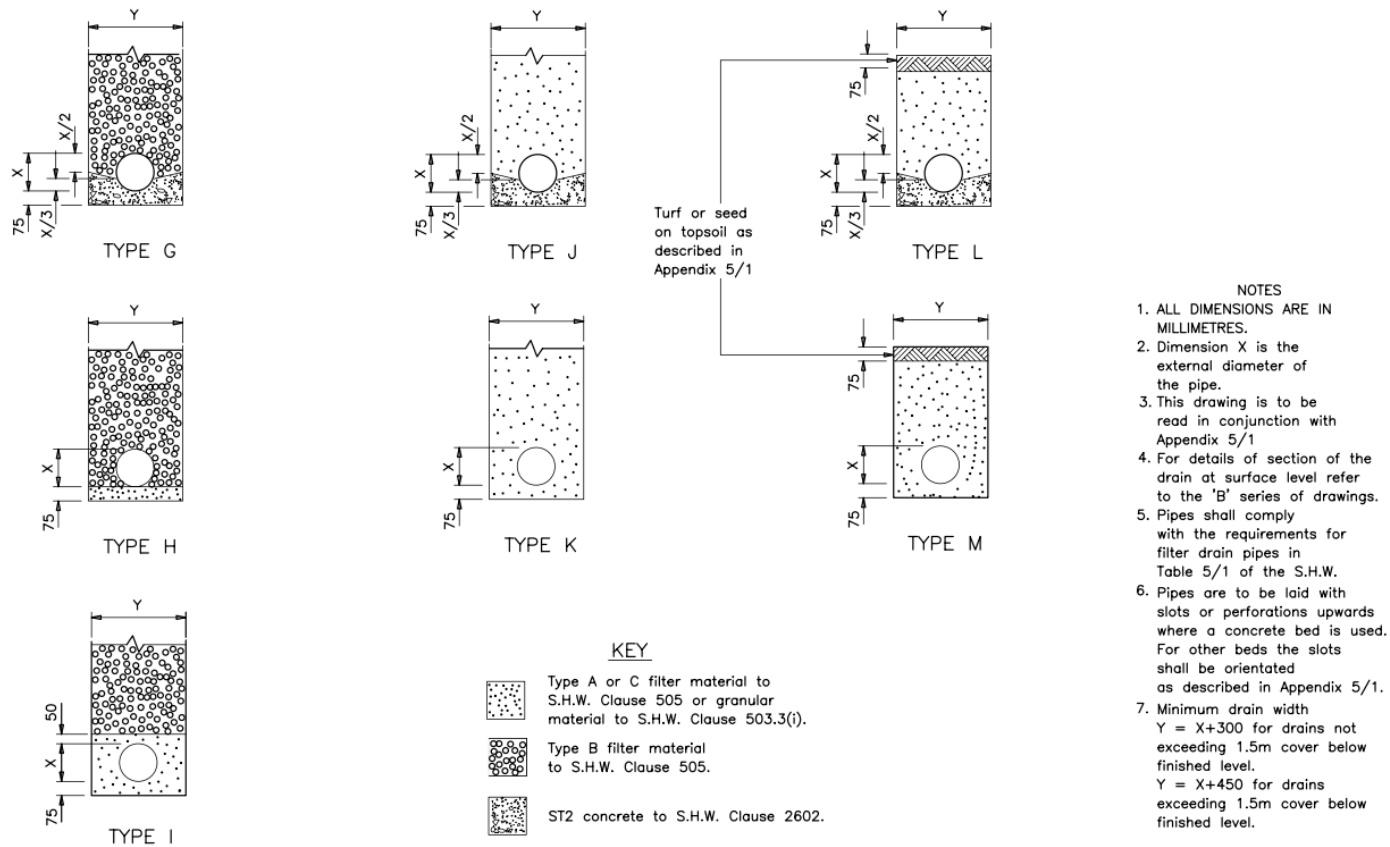


Figure 3 Trench and bedding details used in UK highways (DMRB, Series 500, B-series)

2.2.1.2 Deterioration and Maintenance

HFDs (adopting Type B backfill) are typically characterised as free draining upon construction; however, over time the voids of the granular medium become partially or wholly filled due to the intrusion of fines washed from the adjacent slopes or pavement surface. Filter drain fouling is the term devised to describe the filling of voids and the gradual clogging of a filter drain trench. This fouling results in the reduced performance of the drains as it limits the drainage capacity of the filter material.

Currently there are no standards or guidance to evaluate the level of performance against a quantified level of drain fouling. Even though the fact that HFDs failure is driven by the introduction of foulants into the trenches is clearly identified through technical guides, maintenance standards are deemed inadequate (when compared to standard maintenance systems utilised in different sectors). In some long-term maintenance contracts there is a specified minimum level of permeability performance at their beginning and a minimum requirement for residual life at their end. The justification for these values is not included in the available literature.

The fact though remains; HFDs deteriorate over time and in absolute terms the wider industry is well aware of the process. In NG Series 500, the gradual clogging issue, which relates to the aims and objectives of this project is described as : ‘ *grit from the carriageway may slowly block this type of filter and it may require cleaning or replacement periodically*’ A limited number of studies have in the past addressed the phenomenon but lacked quantitative assessment elements. Rowlands and Ellis (2007) reported an anticipated operational lifetime of ten years – this number should reflect the long term performance of Type B backfilled drains. This number is in line with design standards; removal and replacement of the granular material is then a compulsory requirement. During filter drain field evaluations acceptable

performance of many drains has been observed after 20 years of operation with minimal or no maintenance undertaken. The evaluations have shown there is a differentiation between the service life of Type A and Type B drain aggregate and an implied correlation between aggregate type and modes of failure (Samuel and Farrar, 1988b, Samuel and Farrar, 1989).

Contractual requirements in typical DBFO projects usually dictate performance thresholds across all elements in a given asset portfolio as a function of measured condition indices. A wide range of condition evaluation technologies are thus employed to enable the collection of (usually) quantitative metrics that are used as a proxy for performance (HD 30/08, HD 29/08). Visual surveys are still employed but machine based data are embedded within asset evaluation systems (Deflectograph, Scanner, SCRIM). Performance of HFDs is in contrast currently assessed only by visual means lacking structured assessment protocols and any assessment remains subjective at its best.

Lacking means to project deterioration, visual rating of the surface of the drainage trench will 'enforce' a reactive or cyclic maintenance routine. The reactive approach (run asset to failure), leads to a number of disruptive failure events (i.e. carriageway flooding) which are largely unplanned. A time based remedial regime (ie cyclic maintenance), dependent on the frequency of cleaning, reduces the risk of flooding but inevitably specifies cleaning where it may not be required. Both approaches may eventually lead to reduced value for money through over or under maintenance and limit medium to long-term maintenance planning. A break-down of existing maintenance management systems and approaches can be seen in Figure 4. Here, four main maintenance scenarios are presented each one focusing on a particular type of intervention trigger. A reactive approach is result of identifying drainage failures across a network which in this case will be flooding and water ponding on the carriageway or deterioration due to excess HFD vegetation growth. A risk based approach relates to identification of flooding risk by evaluating risk registers leading to a preventive

type of approach. Contractual requirements can also specify maintenance intervals (ie bi-annual cycles of scarifying, 10 year cycles to replace aggregate) leading to cyclic maintenance or asset hard-time replacement as defined in contracts.

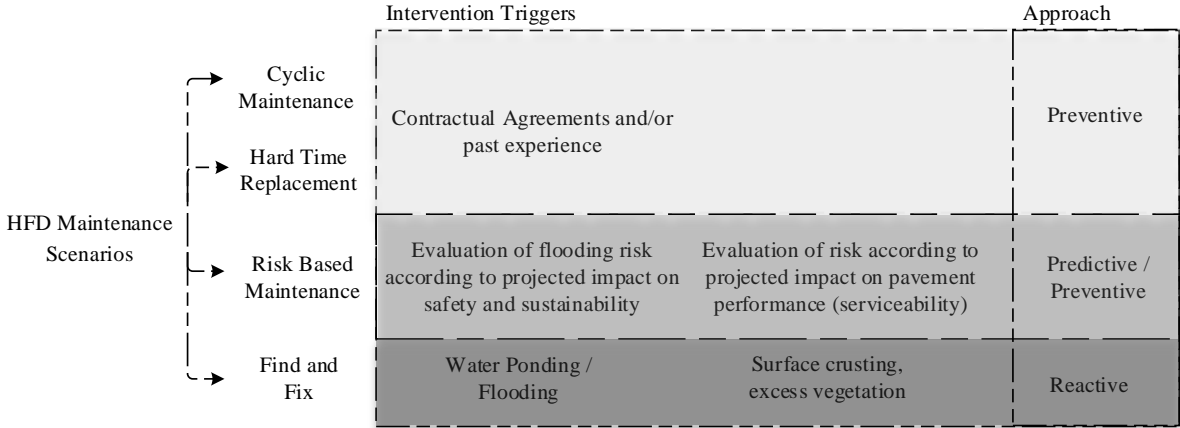


Figure 4 Different types of Maintenance approaches employed for management of HFD across UK roads network

In HA 217/08 a maintenance prioritisation methodology is suggested which identifies the main cause for deterioration as the sediment transportation through the stone aggregate, vegetation growth and vehicular over run. Even though requirements for excavation of trenches, recycling of material and waste disposal are introduced, no specific management guidelines are presented. No quantitative means to evaluate level and extent of fouling are described and no specific actions (maintenance or further investigation) are presented aligned to distress levels. Such an approach can only be described as generic and a facilitator of a rather empirical practice. Visual cues indicative of functional failure include surface ponding or siltation, vegetation growth and visible wheel rutting at the surface of the trench. These indicators describe failure modes associated with the surface layers of the trench. However, water ponding can also be the result of large fouling levels concentrated deeper in the drain. These two different failure modes have been previously observed in HFD field evaluation studies (Samuel and Farrar, 1988b) even though further discussion on how to take this forward and proactively maintain the asset is not really discussed.

Existing maintenance options include filter drain scarifying (and potentially topping up), aggregate removal and replacement or on site rehabilitation/recycling of the drainage fill. The former is probably the most straightforward (and cheapest) option; a scarifier is used to loose the top layers of the trench in order to break down the plastic 'cake' blocking the flow of water through the drain. Essentially no contaminants are removed from the trench but this approach offers a quick and cheap solution that requires no special equipment. The treatment offers acceptable results given investment requirements but in practical terms, it can only tackle reduced performance as a direct result of highly concentrated fouling (or vegetation growth) at the upper layers of the HFD trench. It can also lead to adverse performance in the medium to long term assuming detritus is post-intervention allowed to further penetrate in the trench.

Depending on the extent of deterioration, scarifying coupled with removal of fouling and topping up of the trench has shown to generate good value for money on the A50 DBFO network. Samuel and Farrar (1988b) on their site evaluation report, suggest similar results; by removing the detritus blocking the uppermost of the drainage trench, flow into the drain can be up to 100 times greater. This option is suggested to be more suitable for Type A backfilled trenches, or drains that incorporate sacrificial layers at the top of the trench (usually adopting a geotextile to limit the ingress of detritus to lower parts of the filter medium). Figure 5 exhibits some examples of scarifying exercises on the M77/GSO DBFO and A50 DBFO. The A50 maintenance operations were coupled to fouling extraction and topping up using Type B material; the MAC Operator reports that such an approach becomes more effective if the fouling concentrations exhibit high plasticity. Scarifying problematic HFD sections across the network was thus planned post – light rainfall events.

The second maintenance option prescribes the complete removal of the aggregate material and replacement with a fresh fill straight from local quarries. The depth of excavation usually

varies according to the severity of the drain's condition (again based on subjective condition criteria or extend of flooding events mapped to guestimating extend of aggregate fouling) and obviously, budget availability. The approach comes with higher costs but the replacement of, in most cases, severely clogged aggregate results in an immediate increase of the drain's water carrying capacity.



Figure 5 Scarifying exercise on the M77/GSO DBFOs.

The third and final maintenance option has been introduced in the sector recently as an effort to introduce a more sustainable thinking in HFD maintenance management. The concept is based on cleaning and recycling the aggregate in situ rather than disposing the lot and replacing the fill. The technique has been used around the highway network in the United Kingdom and different contractors offer the same in effect result employing slightly modified tools (examples include the StoneMaster by Carnell and on site recycling by Story Contracting). The cost of adopting the technique is though still considered high in some cases.

2.2.2 HIGHWAY ASSET MANAGEMENT

2.2.2.1 Overview

The shift from the need to continuously expand the public infrastructure portfolio to the need of maintaining and preserving existing assets using scarce and sparse financial resources has stirred up a maintenance paradigm shift in the infrastructure sector. Perceiving maintenance as necessary repair work is now a thing of the past; instead maintenance planning takes a pivotal role in life-cycle planning (Robinson et al., 1998). Investment prioritisation often follows an engineered rationale, and local governments and private organisations operating as custodians of infrastructure networks, have recognised the need for data-driven decision-making. Such an approach is based on quantitative investment criteria and a well-defined and clear ‘line of sight’ between organisational and strategic goals and front-line project delivery and operational support (Vanier, 2001) .

With Asset Management thinking being deployed around the industry to facilitate the need for value-for money investing, optimised lifecycle delivery and decision-making visibility, Management Systems and often asset-specific Decision Support Tools are commonly used to enable short and long term, investment planning. To a lesser or larger extent (and different levels of sophistication(Department for Transport, 2016)) asset custodians are following or establishing asset management activities to enable forward planning, to secure private or governmental funds (e.g. through DfT’s Incentive Funding mechanism), to allocate budgets and to exhibit asset performance in a language that is ‘universally comprehensive’.

There are indeed a number of conceptual models that break down what Asset Management represents. The Institute of Asset Management (IAM) takes the view that there is no single perfect model to describe all that is Asset Management and different organisations can explore and develop and tailor a model that works best for them. The IAM’s conceptual

model comprises of a suite of six Subject Groups covering 39 asset management Subjects and are listed below:

- **Group 1: Strategy and Planning:** Aligns an organisation's asset management activities with organisational objectives – establishes the 'line of sight'.
- **Group 2: Asset Management Decision Making:** Defines challenges of asset management and the approaches in dealing with acquisition / design, operation / maintenance of assets and finally end of asset life.
- **Group 3: Life Cycle Delivery:** Processes that define the implementation of the Strategy and Planning Subject outputs.
- **Group 4: Asset Information:** Activities and elements that typically generate inputs to all asset management processes.
- **Group 5: Organisation & People:** Elements and guidelines that define the organisational structure, culture and context and support the introduction, adoption and delivery of successful asset management.
- **Group 6: Risk & Review:** Core AM activities associated with identifying and managing operational risk (Institute of Asset Management, 2015)

It thus becomes clear that AM is typically founded upon a well-structured framework that is far more complex than a one-fits-all tool. Infrastructure Asset Management is defined as the systematic approach in maintaining, expanding and operating physical assets in the most cost-effective manner drawing from organisational objectives. It is based on comprehensive information and knowledge generation tackling asset investment needs in a holistic and proactive way (Li and Sinha, 2004); being such a complex and multi-faceted collection of activities, tasks, resources, people and information, a universal language is required to normalise the organisational journey to delivering an all-encompassing Asset Management System.

This can be achieved using the recent BS ISO 55000 standards (BRITISH STANDARDS INSTITUTE, 2014) which aim to coordinate and offer a sense of direction and control for all AM activities. ISO 55001 defines 7 sets of key requirements for an AM management system supported by a number of ‘binding statements’ detailing each requirement. These are listed as:

- Define Organisational Context.
- Leadership commitment and direction, and roles and responsibilities.
- Multi-level planning for assets and asset management.
- Support for effective management: resources, tools and information
- Operational control of the management system and dependent asset systems.
- Evaluation of the performance of the management system and dependent asset systems.
- Improvement, including correction and prevention in a quality – process environment.

In a sense, the British Standard details what needs to be done in the wider organisational context to meet minimum requirements for a BSI accredited Asset Management management system. The standards don’t define how this will be achieved though and this is discussed in Paper 2 (Appendix 2 see section 2.3.1 The Building Blocks of AM – a Top Down approach) that presents and details how asset owners such as Local Councils have drawn from the Highways Asset Management Guidance Document (HMEP, 2013) to reinforce the case of AM and deliver benefits from such an approach. The Department for Transport (DfT) - funded guidance document was produced under the umbrella of the Highways Maintenance Efficiency Program (HMEP) and is accompanied by a number of secondary documents and toolkits aimed at lifecycle planning, deterioration modelling and drainage asset management.

A highway maintenance management system can be theoretically broken down in three unique sub-systems to support data acquisition, performance models and knowledge

generation, and lastly definition of investment criteria, optimisation rules and implementation and feedback (Bowditch, 1990). Information flows between each process are continuous thus one will find drawing boundaries between each sub-system a challenging task. Asset management is a ‘staged process’; it is established by first defining the strategic framework that will support the management and operation control of asset-specific schemes. This then enables the derivation of AM goals and objectives taking into account client expectations and contractual requirements. An Asset Management conceptual framework is defined and broken down in Molenaar (2011) and listed below:

- **AM Strategic Planning:** Establish or update objectives, identify resources used to meet the objectives, set up policies governing resources embedded within management system.
- **Management Control – Decision Support tools:** Assure that value generated from resources is maximised en-route to achieving strategic objectives.
- **Operational Control – Program Implementation:** Establish line of sight; ensure highway specific schemes are aligned to strategic and management objectives and carried out in an effective and efficient manner. Identify the right asset, the right intervention and the right timing.

The three-parts framework listed above can be loosely mapped to one presented in HMEP (2013); here the 14 AM recommendations (ranging from development of an AM Strategy and Policy to an establishment of asset data management principles and to the development of a holistic lifecycle planning process) are grouped in 3 main categories:

- **AM Context:** Describes the context of AM, the organisational structure and the environment within which local councils are expected to deliver services.

- **Asset Management Planning:** Defines key activities and processes for AM planning and advocates how these should be applied to different asset classes
- **Asset Management Enablers:** Defines enablers that support the implementation of the proposed framework.

There is consensus among the industrial and academic communities that such a strategic approach to the allocation of resources in maintaining physical assets will eventually result in a significant economic saving (the best buck for the bang). It also leads to a better alignment of operations to client and stakeholder expectations and allows visibility and realisation of asset value (Falls et al., 1994).

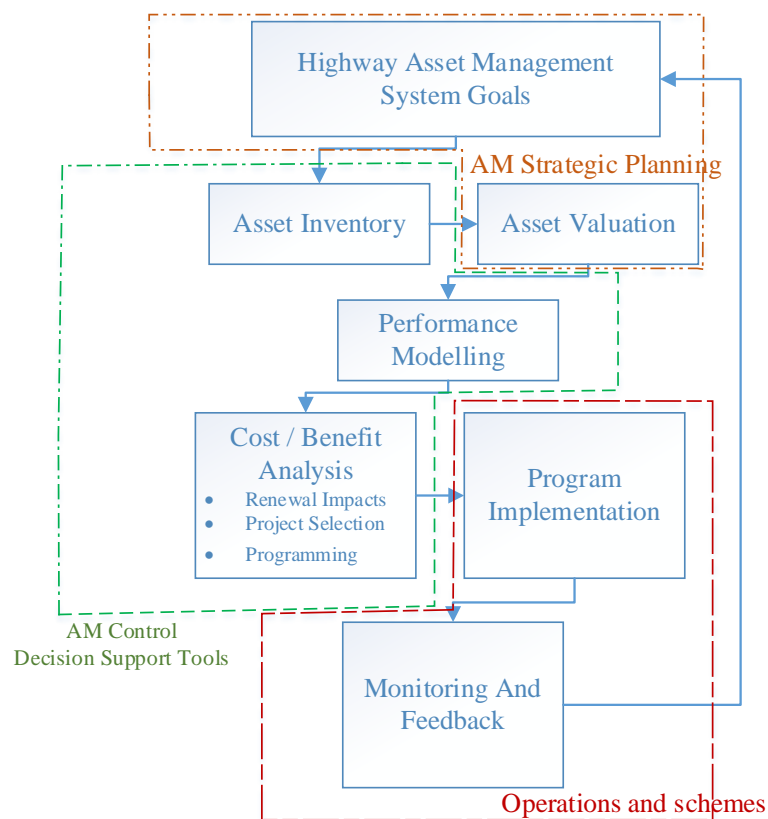


Figure 6 A Generic (Highways) Asset Management Framework (Molenaar, 2011)

Drainage specific asset management elements are the focus of two key publications that define the founding principles for a shift to proactive lifecycle planning. Spink et al. (2014)

offer a series of guidelines focusing on condition evaluation, maintenance and rehabilitation of drainage infrastructure, as well as advice on issues such as inspection and monitoring and environmental issues.

The second publication, HMEP's guidance on the management of highway drainage assets, draws from the AM framework proposed in HMEP (2013) – Highway Infrastructure Asset Management, and sets 14 drainage specific recommendations grouped into 3 main themes (Defining the Asset, Service Delivery, People and Partnerships). The guidance identifies how asset data are crucial for the development of a robust and efficient drainage management approach as a means of prioritising maintenance and rehabilitation schemes. Both documents discuss flooding risk and present case studies of adopted risk-based data collection approaches and risk driven maintenance investment planning. Such an approach can potentially significantly reduce drainage performance shortfalls but may in cases lack the contextual framework to enable the evaluation of the asset's physical condition as further discussed in Paper 2 (see section 2.2 Defining Maintenance and Maintenance Strategies).

2.2.2.2 Management Data and Information

2.2.2.2.1 Overview

Infrastructure management systems are data centralised; any type of decision-making is the result of evaluating up to date, reliable and appropriate information. In a generic form, types of asset information that are often included (or perhaps should be included) in any asset management system are listed below and diagrammatically presented in Figure 7:

- Inventory data; a description of the physical assets to be included in any analysis
- Condition data; a database that enables evaluation of physical assets
- Maintenance history data;

- Maintenance rules; a definition of treatment triggers and treatment impacts
- Maintenance Costs (Ryall, 2001)

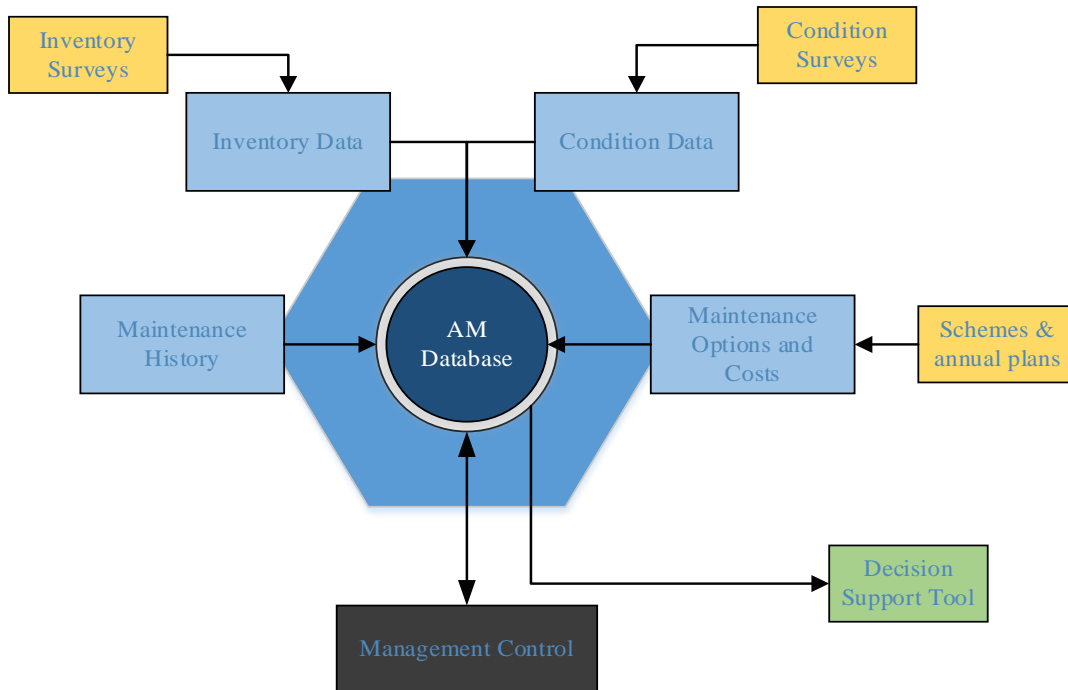


Figure 7 Types of information held within a typical AM Database

To enable efficient optimisation of resources allocation and maintenance planning one needs to be able to establish predictive capabilities linked to the numerous available courses of action (i.e. the maintenance and investment strategies). While such capabilities can obviously be linked to condition and physical inventories they are in most cases supplemented by information linked to strategies, environmental conditions or anything that may affect managerial decision making (Haas and Hudson, 2015)

Management information including the aforementioned types of data can become quite costly; data collection and database management is a task that requires large capital investments. Asset custodians are thus expected to evaluate trade-offs and balance data acquisition and management costs with the anticipated value generated from such tasks. Data can be used to support any kind of decision making be either evaluating current levels of service or

appropriate investment profiles, maintenance costs and optimised life-cycle strategies. Within the spectrum of proactive maintenance asset information is used as the intermediate between technical and financial departments sitting at the heart of decision making (Robinson et al., 1998).

2.2.2.2.2 Information Levels

Asset Management Systems take functional form when they are dimensioned into two operating levels: network and project. Data collection processes, data management and interpretation, condition evaluation, decision making and budget allocation take place at each level and inputs, information quality and analysis are tailored according to the outputs sought (Haas, 2001, Zhang et al., 2013).

Strategic decision-making, allocation of annual budgets and overall strategy generation takes place at the network level hence data is needed for each segment in a given roadway network. Project level decision making is ‘scheme-specific’, focused on individual projects and deals with overall program implementation. In simple terms, network level deals with a ‘bird’s-eye’ view of a network while project-level specific actions, relate to the detailed implementation of network decisions. To meet performance requirements and achieve this in a financially viable and sustainable way, the two levels are aligned and streams of data synchronise strategic planning and actual implementation of network level decisions(Uddin et al.).

For large infrastructure systems dealing with various asset categories (pavement, structures, congestion, drainage, traffic) each functional level plays an important role in strategy generation and program prioritisation. The development and evaluation of data factorises information quality levels (i.e. how much is invested in data collection to describe and evaluate a specific asset or section) according to data suitability, costs and data availability. In most cases the two functional levels come together in a type of integration platform – GIS

systems, excel spreadsheets or other IT systems capable of holding, managing and updating information. An overall breakdown of the two levels along with data embedment and data streams is shown in Figure 8 (Haas, 2001).

For DBFO projects dealing with specific highway sections across the UK trunk road network, the boundaries between the two levels are somewhat blurred. A distinction can be made between overall network and scheme specific project level, but in reality, asset portfolios are created bottom-up, incorporating detailed information for any pavement section or structure in a given network. While from Connect's perspective investment requirements are presented at the network level at annual WLP board meetings, this is a result of optimising scheme selection at the project level first. Within the same AMS database, all 'competing' asset groups become part of the optimisation problem that focuses on minimising maintenance expenditure profiles under the 'scrutiny' of performance requirements. In a sense, project level analysis comes into play once scheme selection becomes a function of site practicalities and Traffic Management allocation across a network and this further enhances the generated Whole Life Plan allocation of funds. Typical considerations at this point of maintenance-spent allocation are often unrelated to asset condition and performance and tend to be a function of socio-political expectations or secondary geographical limitations. A further discussion of this process is broken down in subsequent chapters (see Chapter 4 Research Undertaken).

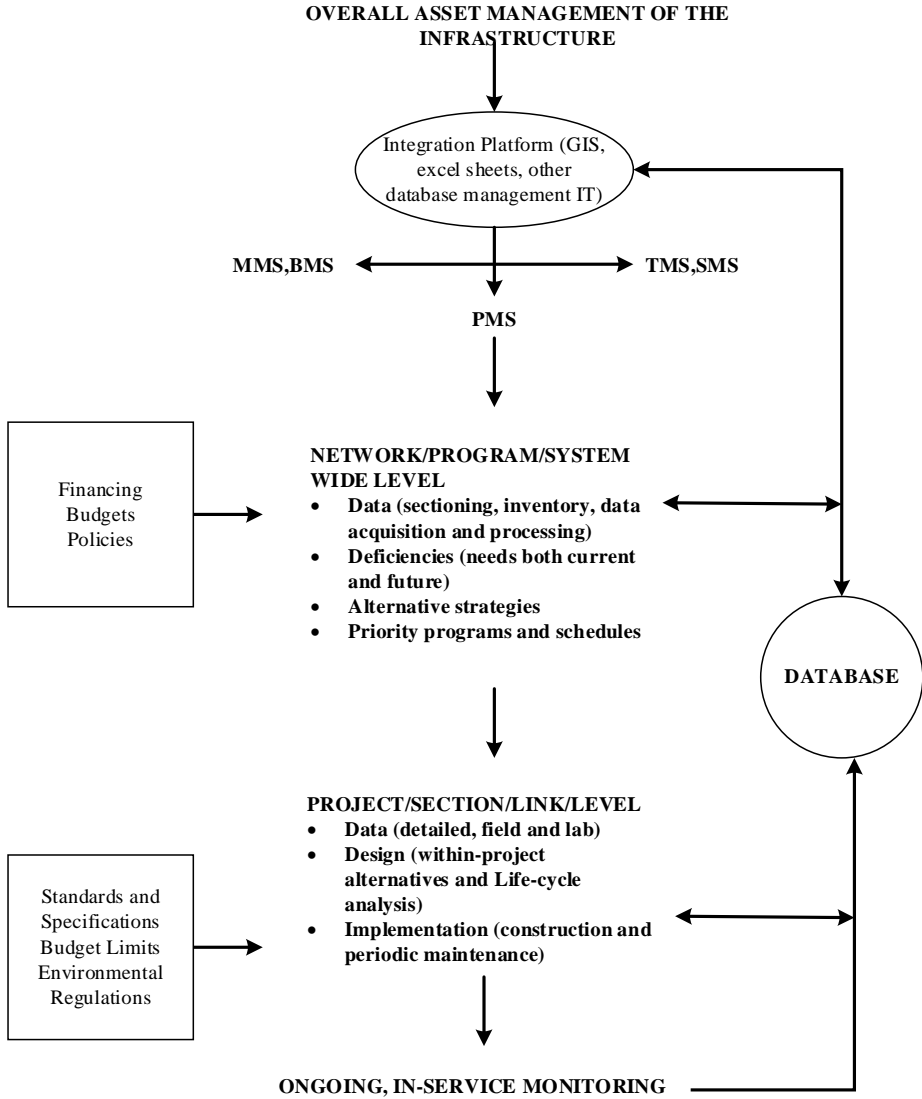


Figure 8 Overall breakdown of network and project level data and processes as presented in Haas (2001)

2.2.2.2.3 Inventory and Condition data

Inventory data tends to be collected only once to support the development of an asset specific management system (be either pavement, bridges or drainage); updates are introduced if new assets (i.e. new pavement sections or new structures) are embedded within an existing management system or major reconstruction projects take place. In pavement DSTs pavement construction details, location (geo-referencing), and design traffic loads are some examples of data that are used to build the initial database. Such exercises once completed support the continuous operation of DSTs and implementation of the AM strategy.

Information that is usually updated on annual basis (or following pre-established schedules) is tend to be generated by condition surveys. Physical assets deteriorate with time; pavement serviceability, structural capacity and safety performance will change and a number of different evaluation techniques have been established to quantify this. Such techniques form Condition Assessment Systems that are central pieces to any AM protocol (Marlow and Burn, 2008). Condition evaluation techniques can be broadly classified as:

- Destructive:

Methods and processes of obtaining further information about the internal characteristics of an asset by in-situ testing and by retrieving and testing samples from the asset. They normally involve studying the internal parts of an asset by excavation, boring, or probing methods. Available methods can be have low levels of intrusion (not affect the integrity of asset as a whole –semi destructive techniques) or can be very intrusive and may not be suitable where continuous integrity is required (Ogunyoye et al., 2004)

In pavement studies Robinson et al. (1998) explain that destructive methodologies and are often used to identify material properties of the different pavement courses and of the pavement subgrade. In line with the two AM functional levels (Network and Project) destructive testing in road networks is employed at the project level; while detailed and accurate such an approach can be costly and disrupting and probing or excavating across a large network can't be justified in realistic terms.

- Non-Destructive:

NDT&E methods can facilitate three distinctive requirements: detection and characterisation of discontinuities/defects, determination of quality of manufacturing, and assessment of degradation of components during service. Due to the large number of available tools and the plethora of materials and parameters that can be considered in any NDT, applications have

been used in a wide spectrum of scenarios, ranging from the construction industry to the manufacturing sector etc. NDT&E methods provide a number of strong advantages over conventional evaluative techniques, including increased efficiency, improved performance reliability and opportunities for on-line testing or monitoring, the latter being a necessity for an operational preventive maintenance scheme (Raj, 2001).

Nearly all methods employed, involve an emitter and a medium which is excited by the external form of energy (x-rays thermal / mechanical waves, ultrasonic etc). The reflected signal can then be interpreted through pre/post processing under standard recognition patterns. The most obvious and essential feature of NDT is that the procedure itself produces no deleterious effects on the material or structure under test. With conventional infrastructural testing procedures, data for analysis are usually obtained from predefined test parts or core samples; this might produce onerous results, as evaluation can be extremely localized and discrete. Non-destructive testing has the advantage of a rapid and continuous evaluation of an asset able to provide a reliable assessment of its fabric. This will effectively produce saving in time, cost, remedial works and disruptive maintenance(Clark et al., 2004)

In the UK, pavement condition is assessed using a combination of machine based surveys and visual condition investigations. TRACS (Traffic Speeds Condition Surveys) and SCRIM (Sideway-force Coefficient Routine Investigation Machine) are the two main pillars of (non-destructive) condition assessment on the trunk road network offering information for both safety performance (skidding resistance) and pavement serviceability (ride quality). Structural capacity is most commonly evaluated using deflection measurements combined with knowledge of pavement layer thickness. A different non-destructive testing technology commonly used in the UK roads network for inventory database updates and condition evaluation is the ground penetrating radar (GPR). The GPR enables the investigation of

objects hidden by opaque barriers and operates by utilising the electromagnetic (EM) spectrum; the technique is further discussed in Section 2.2.4.2.4 and Papers 2 and 4.

Ground penetrating radar (GPR) is an electromagnetic non-destructive evaluation tool with numerous applications in the civil engineering domain; applications can be found across the sector and may include investigation of construction materials, pavements, bridges and railway track-bed. Early applications of the sensing method can be retrieved in literature dating back to late 1950's (El-said, 1956). The GPR has since grown in use in the transportation sector as a means to meet the increasing demand for asset condition and construction information data collection.

In a typical application, antenna emits an energy pulse that travels downwards in a medium that is evaluated until it meets an object, or a second medium that has different electrical properties than the first, at which point it is scattered or reflected. Evidence of the bouncing signal is collected by a receiver along with the unique travel time required for the pulse to travel from the antenna to the receiver. As a result, reflections will reach the receiver at different times; the time interval required for each wave to travel from the transmitting antenna, through the medium and a reflection to be picked up by the receiver is called the 'two-way' travel time (Δt) – see Figure 9. When recorded amplitudes are plotted as a function of time, a GPR 'trace' is generated (Annan, 2009, Koppenjan, 2009).

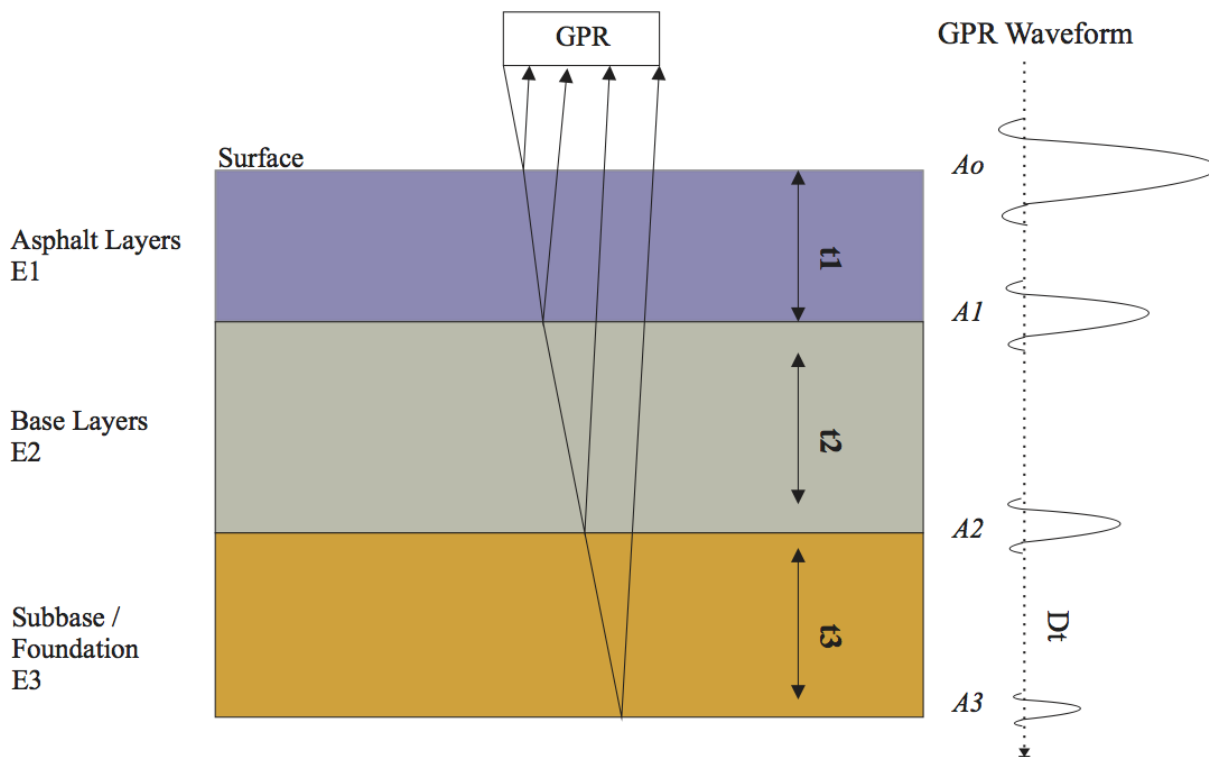


Figure 9 Propagation and reflection of EM pulse traveling in a pavement section. Amplitudes generated at boundaries between materials with interchanging material properties

The propagation velocity (u) at which the wave travels through the medium is a function of the relative permittivity ϵ , generally a material property. The velocity is hence calculated using:

$$u = c/\sqrt{\epsilon}$$

$c = 0.3m/ns$ represents the EM wave's travel velocity in air (same as in vacuum) which is equal to the velocity of light. This will be lower when traveling through any medium other than vacuum. The wavelength (λ) of the incident wave inside a medium is related to the frequency (f) and the EM wave velocity so that:

$$\lambda = \frac{u}{f} = c/[f\sqrt{\epsilon}]$$

If the propagation velocity through a given medium can be extracted (or estimated), the medium's depth (r) can be calculated using the recorded two-way travel time according to:

$$r = (u \times \Delta t)/2$$

Ground or air-coupled systems have been used in the UK for pavement (Evans et al., 2008, Gordon et al., 1998, Saarenketo and Scullion, 2000) or railway track-bed studies (Brough et al., 2003, Eriksen et al., 2004, Roberts et al., 2008, Leng and Al-Qadi, 2009a). Ground systems require the antenna unit to be in direct contact with the scanned medium dictating low survey speeds and even surfaces (thus lane closures and traffic management for pavement studies and risk of damaging the GPR unit in ballast surveys). Air coupled system are mounted at approximately 0.50 m above ground on the back of a survey van to allow for highway-speed surveys and reduce traffic management requirements. The antennae are usually horn shaped and have frequency bandwidths ranging between 500MHz and 2.0GHz that offer different depth penetration capabilities in different materials.

A number of different data processing approaches have been developed over the years to tackle different condition evaluation objectives. These generally vary as a function of the structure being evaluated and the evaluation objectives. Pavement studies are more focused in the signal's time domain. The data processing is thus concerned with the evaluation of signal's peak amplitudes and two-way travel time. Extracting this information can relate back to pavement layer condition (Smith and Scullion, 1993) or pavement construction information (a task that also allows the generation of asset inventories) (Al-Qadi and Lahouar, 2005a). Standard recognition patterns can also be used to infer back to specific deterioration modes and pavement distress. Pavement voiding (Chen and Scullion, 2008), cracking (Popik and Redman, 2006b) and stripping (Saarenketo and Scullion, 2000) have been identified in GPR studies.

GPR systems with central antenna frequencies ranging between 400MHz and 2GHz have been successfully used in a number of studies to map ballast quality, determine extent of fouling and generally determine track-bed conditions and moisture presence (Zhang et al.,

2011, Carpenter et al., 2004, Hyslip, 2007). Ultimately, GPR users aim to evaluate and align particular characteristics of the reflected wave to ballast specific distress patterns. This has been achieved by either using time domain analysis and often qualitative evaluation of recorded radargrams (Gallagher et al., 1999, Jack and Jackson, 1999), evaluation of the scattering response of the EM signal (Zhang et al., 2011, Al-Qadi et al., 2005) or breaking down and studying the frequency components of the trace (Leng and Al-qadi, 2009).

In the time domain again, the dielectric constant of the ballast – fouling mix has been proposed as a deterioration indicator for maintenance decision making (Gallagher et al., 1999). Absence of clearly formed basal reflections and wave penetration depth (all decreasing with increasing fines migration through formation (Carpenter et al., 2004)) have also been used as a means of ballast condition assessment (Jack and Jackson, 1999). By identifying the ‘footprint’ of the fouling material on the EM wave propagation characteristics, dielectric properties of ballast samples in different fouling and water content levels have been extracted in a number of laboratory based studies (Clark et al., 2000, Fontul et al., 2014, Suits et al., 2010). These studies usually draw information from relevant ballast maintenance-management libraries to suggest fouling extent thresholds (aligned to anticipated levels of service) and extract a relevant dielectric constant range to be fitted within these thresholds. Dielectric constants have been found to vary (2 to 4.1 for dry fresh ballast material) based on the aggregate material selected for analysis, levels and types of fouling, moisture content and antenna type and central frequency used in each study (Leng and Al-Qadi, 2010, De Chiara et al., 2014).

Significant reflections arising from within the initially large void space of the ballast medium have been used as an alternative in-situ ballast condition assessment approach (Al-Qadi et al., 2005). Scattering is a process where EM radiation (or other forms of radiation or sound) deviates from its initial propagation trajectory due to irregularities in the propagation medium.

When localised objects in a medium are of a size similar to the scale of the EM wavelength, a distinctive scattering response from these objects will be ‘amplified’ in a typical radar-profile. Three scattering types exist; these are Rayleigh, Mie and Geometric and they depend on the ratio of the wavelength of the incident signal (a function of central antenna frequency) to the circumference of the inhomogeneity in the medium (Zhang et al., 2011).

For ballast layers the ‘propagation medium’ is assumed to be comprised of the individual ballast aggregate matrix whereas the role of the local scatterers is fulfilled by the available air voids. The normalised dimension of the air voids (D^N) causing scattering can be found in Al-Qadi et al. (2005):

$$D^N = \frac{\alpha\pi}{\lambda}$$

where λ is the wavelength of the incident wave and $\alpha\pi$ is the circumference of the air void scatterer. When non-uniformities are much smaller than the incident wavelength λ , the scattering response falls within the Rayleigh region. If the object dimension approaches the same size as the excitation wavelength, the response falls within the Mie Region and lastly Geometric scattering occurs if scattering particles are much larger than the EM wavelength.

The response enhancement produced through resonance at the Mie region has been identified in GPR scans and has been used as a qualitative or quantitative evaluation of the available void space in a ballast layer in a number of academic publications. In a study presented by Al-Qadi et al. (2010), the application of a trace amplitude envelope is used to extract information from layers that would be missed if a low frequency antenna was selected (a 2GHz antenna is adopted in the study). The authors exhibit how the change of air voids volume in the medium can be used to infer to a degree of fouling in a given section as a function of the ‘intensity’ of the scattering response. The same principles are adopted by Roberts et al. (2007) and Al-Qadi et al. (2008), to present evaluation studies of railroad ballast, subballast and subgrade in either

field of laboratory trials proving that the concept may add value to condition assessment studies.

A detailed literature review focusing and evaluating both state of the art and state of practise in regards to GPR applications is presented in Papers 3 and 4 (Appendix C, Appendix D). Here a discussion of the aforementioned assessment techniques is detailed and geophysical evaluations options drawing from ballast and pavement studies are articulated for the purpose of HFD condition data extraction.

2.2.2.3 Asset Deterioration Modelling

Physical assets are subjected to gradual (and continuous) deterioration being exposed to environmental conditions and loading or usage. There's no question and arguably no method to avoid the inevitable; assets deteriorate over time and deterioration modelling aims to capture and quantify this phenomenon in a way that asset custodians can proactively assess maintenance requirements and budget needs.

The deterioration of infrastructure assets is a complex, multi-faceted problem; bridges and roads face aggressive environments and ever increasing traffic loads. A big number of variables is often factorised to determine deterioration rates and loss of service and deterioration modelling techniques can range in complexity. Uddin et al. (2013) define a staged approach to determine the wide spectrum of activities related to modelling and these are:

- Physical observations to depict asset behaviour
- Mathematical models to define or approximate asset behaviour
- Development of a system integrating mathematical models
- Physical realisation of the system

In terms of pavement evaluation and maintenance assessment, different projection methods have been developed and used in the past. The existing approaches can be grouped into two wider types:

- **Stochastic:** Asset ageing is calculated using probability functions. Survival curves or Markovian probabilities can be used to determine deterioration projection. With probabilistic models it is possible to predict more than one performance level at each point of time. Continuous or discrete functions can be adopted to represent deterioration as a function of time and uncertainty can be incorporated in the analysis (Thompson and Ford, 2012)
- **Deterministic:** Asset ageing is calculated using mathematical functions linked to observed (rated or measured) deterioration. Fundamental properties of the pavement structure, regression models, historical data and data fitting can be used to establish models predicting pavement performance (Jiménez and Mrawira, 2012).

Probabilistic methods can be employed at the project or network level. In the former case they offer information in regards to the probability of a road section moving to a specific condition grade at a given point in time. At the network level they are used to predict the overall network condition using a predefined range of discrete condition states (Ortiz-García et al., 2006).

Discrete probabilistic modelling takes the form of Markov chains that integrate transition probability matrices to represent rates of change of condition, a technique that has been widely adopted to depict the deterioration of infrastructure systems in modern times. A mathematical representation of deterioration is built assuming that the future condition state of any given asset depends only on its current state (Frangopol and Liu, 2007a). The models are established upon estimating probabilities that an asset will move from condition state i to

condition state j and a number of different methodologies have been used to determine such probabilities and cover any uncertainties. Such methods may include evaluation of historical data, expert knowledge or a combination of the two options (Li and Sinha, 2004).

At the beginning of its operational life a pavement should be at or near perfect condition. A number of different condition states can then be defined (i.e. the Pavement Condition Index - PCI ranging from 0 for poor to 100 for excellent condition) to represent discrete points throughout a section's service life. The initial state of the process is defined using a base vector a_o

$$a_o = (a_1, a_2, \dots, a_n)$$

n represents the number of condition bands used in the analysis. Since a_o is a breakdown of all discrete condition states of all assets in the network, values for entries in the vector are non-negative and summed up they account to 1 (or 100% of the network). To simulate ageing (change of condition as a function of time) a TPM is adopted to hold the information that relates to deterioration rates and transition probabilities between states. In general form a TPM (P) can be denoted by:

$$P = \begin{bmatrix} p_{11} & p_{12} & \cdots & p_{1n} \\ p_{21} & p_{22} & \cdots & p_{2n} \\ \vdots & & \ddots & \vdots \\ p_{n1} & p_{n2} & \cdots & p_{nn} \end{bmatrix}$$

p_{ij} denotes the probability of a given section to move from state i to state j in a time cycle which is usually assumed to be one full traffic year. The number of rows in the table is now equal to the discrete condition states represented in the model. Similar to the base vector, a transition probability matrix should satisfy two conditions:

- Sum of each row should be equal to 1
- All entries are non-negative

If for example an assumption can be made that pavement condition cannot move by more than one step in a service cycle and five discrete condition bands can be used to describe pavement condition, then in each analysis pavement sections will either remain in their current state or move to the adjacent ‘lower’. The TPM can then be formulated as shown below:

$$P = \begin{matrix} & \begin{matrix} i & j & k & l & m \end{matrix} \\ \begin{matrix} i \\ j \\ k \\ l \\ m \end{matrix} & \begin{bmatrix} p_{ii} & p_{ij} & 0 & 0 & 0 \\ 0 & p_{jj} & p_{jk} & 0 & 0 \\ 0 & 0 & p_{kk} & p_{kl} & 0 \\ 0 & 0 & 0 & p_{ll} & p_{lm} \\ 0 & 0 & 0 & 0 & p_{mm} \end{bmatrix} \end{matrix}$$

The condition distribution of the network at a specific time t can then be calculated by multiplying the base vector (a_o) by the TPM raised to the power of t . In Years 1 and 2 the table breaking down condition distribution across the network (a_1, a_2) will be:

$$a_1 = a_o P$$

$$a_2 = a_1 * P = a_o P^2$$

Subsequently:

$$a_t = a_o P^t$$

Numerous examples of Markov chains’ applications can be retrieved in the academic field (some detailed above) but also in current state of highway practise. The HMEP guidance document (HMEP, 2012b) offers a lifecycle planning toolkit which embeds transition probabilities matrices to project deterioration for pavement materials and enable future maintenance needs projection. The toolkit can be used as a network level DST to enable Local Highway Authorities to make decisions regarding the timing of future maintenance alternatives and develop and review strategic plans and their likely impact.

2.2.2.4 Treatment Selection and strategy generation

If a particular asset is not performing at an anticipated level of service then it is due for maintenance, rehabilitation or replacement (current needs). Future investment requirements

(future needs) are calculated in the basis of adopting deterioration projection and evaluating serviceability at future points of time. While material requirements and the necessity to maintain infrastructure will never halt, resources and budgets tend to be limited. The scarcity of funds imposes the need to define means of prioritising renewal schemes according to rational priorities.

Prioritising projects is according to Uddin et al. (2013) a four step process:

- Data acquisition
- Processing and information generation
- Determination of current and future needs
- Priority analysis and results

A few options have been used to enable investment prioritisation; some more complex than others offer results than can be expected to be near optimal, others based on ranking and subjectivity may lack such quality outputs. In effect, all approaches should converge to the same type of outputs:

- Which asset requires treatment
- What kind of treatment should be used
- When should the treatment be applied
- What is the effect of the adopted strategy

Prioritising based on ranking is usually employed at the network level. Without integrating an element of multi-year evaluation such an approach may be quick and simple but comes with the disadvantage of embedded subjectivity and can only be the basis for short to medium strategy formulation. There's also no indication of the effectiveness of the adopted maintenance strategy as different scenarios are not really compared against all possible

outcomes. Robinson et al. (1998) group such prioritisation options as first generation methods. Maintenance requirements for competing projects are established and are then ranked and listed according to some form of priority – usually degree of defectiveness. Once the budget cut-off line is drawn, annual work plans can be generated. Projects that have failed to be included in the funded project list are deferred and reconsidered in the next planning cycle.

Some sophistication in the ranking process can be embedded in the analysis in the form of road section importance (road types or traffic levels), and reserved maintenance budget allocations (Sharaf, 1993). Such techniques remain though largely subjective (even though engineering judgement can be applied at some level), lack a view of the ‘bigger – picture’ and of a comprehensive view of a specific strategy’s long-term network effects. They are also reported to be subpar and in most cases generate increasing maintenance investment requirements.

In recent times, maintenance management and effective allocation of resources has mathematically been defined as an optimisation problem. An objective function depicting the primary aim of the problem (life cycle cost minimisation, performance maximisation) can be used along with constraints linked to structural / serviceability performance requirements and life cycle cost limitations. (Frangopol and Liu, 2007a, de la Garza et al., 2011). Different types of aims can be established for such a method. Examples may include:

- Minimise annual and total maintenance sum of costs to the road administration and road user subject to constraints of:
 - Performance standards
 - Maximum budgets (total and/or annual)

- Maximise road conditions over planning horizon (analysis period) subject to a predefined budget (Finn, 1998)

Methods to solve the objective function include linear / nonlinear programming, heuristic methods (genetic algorithms - GA) and dynamic programming. The use of GAs in optimisation has also lead to the use of multi-objective functions, which combine in a single optimisation problem competing objectives that should all be maximised or minimised. These techniques remain outside of the scope of this work primarily because of Connect's proprietary DST (dTims) that handles maintenance prioritisation through pre-defined system algorithms. Further information and applications of GAs in pavement maintenance investment optimisation can be found in (Morcoux and Lounis, 2005, Frangopol and Liu, 2007b).

2.3 GAPS IN THE LITERATURE

There is a consensus within the infrastructure sector that AM represents a set of tools, ideas and systems developed to align high level organisational goals to operational activities dealing with asset maintenance, renewal and expansion. Asset Management does not replace good practise; it instead represents good practise by rationalising and unifying such elements as asset knowledge, condition assessment principles, performance modelling and strategy generation. Such a systemised approach is defined by and revolves around asset data and knowledge generation.

Pavement Management Systems (and in similar fashion Bridge or Maintenance Management Systems to some extent) form parts of an all-encompassing AMS strategy, have been briefly discussed in previous sections. This to enable the identification of the means and methodologies that need to be transferred to HFD management in order to achieve the establishment of a proactive and engineered maintenance thinking.

Under current business models, planned HFD maintenance often tends to be passive or reactive, based on empirical evidence in a given network with little formal long-term planning of investments or life-cycle cost projections. Strategies (if generated at all) can be a function of short-term costs rather than sustainable planning and long-term efficiency. Any divergence from initial assumptions (higher running costs than original funds allocation), can be covered using either transfers from other sub-heads (based on availability), a do minimum-approach or through the maintenance reserve account established for unexpected failures in a concession (through Board's approval if risks are too high and unavoidable). This is largely due to the lack of a structured framework to enable road operators to collect and process condition data and the fact that dealing with drainage systems in the highways sector has not in the past been

integrated in holistic Asset Management (AM) plans. This maintenance model generates the 'reactive maintenance cycle' depicted in Figure 10.

Condition data, a key input in any management system, enables the evaluation of the current physical state of an asset, allows the generation of performance indicators (from metrics to levels of service) and the identification of current maintenance backlogs and future maintenance requirements. A condition database can be used to project deterioration and establish asset maintenance and rehabilitation (MR&R) needs and future strategies. There is obviously more to an AM framework than just evaluating condition but given the existing maturity levels of proactive management systems dealing with various asset groups in a typical highways network, condition evaluation and monitoring will probably be the biggest challenge in developing and introducing proactive HFD maintenance planning.

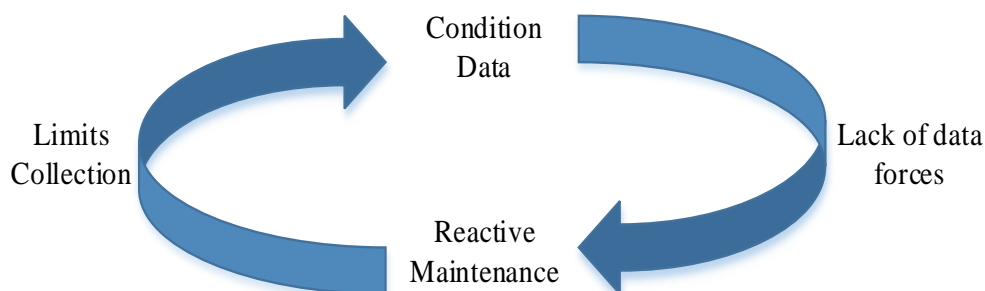


Figure 10 Cause and effect - the HFD reactive maintenance cycle.

2.4 SUMMARY

This chapter presented an extensive review of HFD literature and existing maintenance practices. Current deterioration thinking is described along with existing maintenance management techniques employed across the UK roads network. A breakdown of AM thinking and principles is also presented in an effort to identify key elements required to formalise a similar approach for a HFD-specific management system. Key components are thus detailed and these include data (inventory, condition, maintenance costs, historical

maintenance), methodologies (inventory collection, condition assessment) and data processing (deterioration modelling, prioritising). The research methodology employed to tackle the literature gap and produce the required novelty is now presented in Chapter 3.

3 ADOPTED METHODOLOGY

3.1 INTRODUCTION

Within this chapter, the term methodology is used to define the approaches adopted to complete the various tasks and work-packages introduced for the completion of the EngD project; in principle, the term defines the way(s) adopted to systematically solve the research problem as formulated by the research centre, the RE and the industrial/academic supervisors. It also defines the scientific framework required to support the introduction of the various research methods used to conduct the research into the project.

In a nutshell there are two main types of research routes; qualitative and quantitative. There is a general consensus on what each approach represents and what are the merits and what the limitations of each option. A quantitative methodology is expected to generate numerical data or information that can be easily transposed to numbers. In contrast, qualitative research focuses on non-numerical information often synthesised in an interpretative or subjective manner. A third type of research, mixed-methods is an approach to inquiry involving collecting both numeric and non-numeric data, integrating the two and using distinct designs that may involve philosophical assumptions and theoretical frameworks.

For this particular EngD project all three approaches have been used to some extent to meet the requirements to develop the sub-routines embedded within the MM proactive approach brought forward. The work focused early on, on evaluating the state of the art through British ISOs, Design Manuals and academic work targeting pavement and asset management. This led to the reinforcement of the research question and the identification of the needed area of inquiry. Research methods were articulated as a function of project objectives and these supported the project tasks defined in the following sections.

The nature of the research work combines in itself elements that required structured laboratory methods to be developed to accommodate the adoption of innovative HFD assessment protocols (quantitative research) and evaluation of current pavement management practise through CR (qualitative – mixed methods). The later enabled the formulation of the management system’s structure while the former brought forward the means and techniques required to collect the relevant asset information. It is perhaps easier to identify the methodological routes and intended outcomes derived to support the research aim by considering the four publications produced from this work. Their alignment to both research objectives and undertaken tasks can be observed in Figure 11.

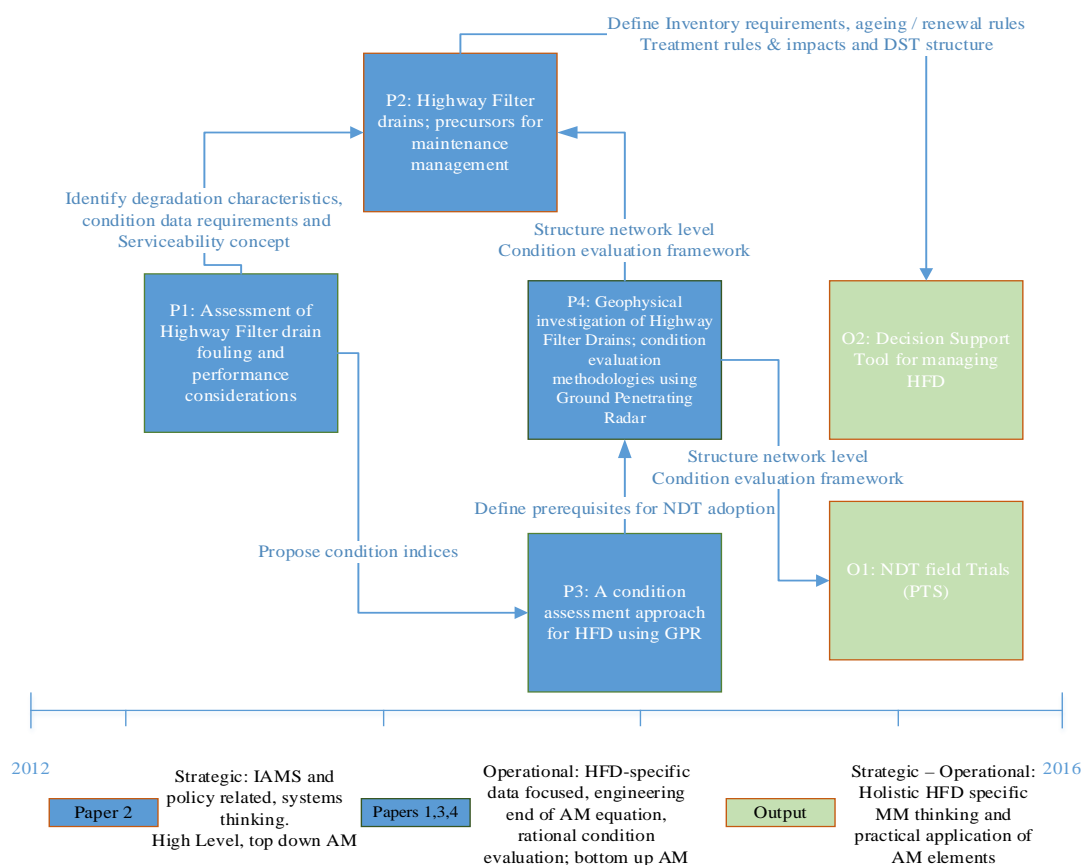


Figure 11 Breakdown of four year main research outputs including publications and MM toolkits

3.2 RESEARCH APPROACHES AND METHODS

The three main research methods employed to support all research tasks are summarised below:

- **Open - ended discussions & case studies**

While the initial objectives set by the industrial sponsor focused on the development of condition assessment routines and monitoring techniques, a holistic management approach should prioritise a ‘bottom-up’ systemised management framework. Such a framework integrates at its core elements that revolve around asset inventory requirements, condition assessment principles, deterioration modelling and evaluation of what-if scenarios. The HFD management approach developed should embed such elements tailored to the business requirements of the industrial sponsor; it was thus identified at an early stage that a breakdown of the sponsor’s approach to pavement management should be further evaluated and the aforementioned HFD Maintenance Management system to adopt and follow Connect’s pavement life-cycle planning process.

To thus structure and define the way forward and ‘modus operandi’ of the MM framework, information and knowledge was collated from published literature (design manuals, drainage technical guides), Connect Roads PM business cycles, continuing interaction with CR’s AM team (expert views) and discussions with governmental bodies (Highways England, Transport Scotland). Hypotheses were established as a function of individual objectives to lead to the formulation of a MM framework. Some examples included:

- H1: Can proactive thinking be adopted for HFD MM
- H2: Can pavement evaluation protocols be transposed to HFD thinking,
- H3: Can a probabilistic modelling approach be used in HFD management,
- H4: Can asset data be used to structure a HFD DST.

- **Experimental work**

Pertaining to the evaluation of serviceability levels and condition evaluation principles brought forward from this work, a series of controlled (laboratory based) and field studies were planned and undertaken. These formed the objective research milestones and the basis to develop the analytical tools to supplement the MM framework under development. The experimental work focused on validating findings and proposing key outputs on the basis on interrogating a set of established hypotheses founded upon factual data in a quantifiable manner.

Much like for the first set of research methodologies, Hypotheses were established as a function of individual task objectives. Some examples include

- HE1: Can a HFD condition descriptor be defined,
- HE2: Can serviceability levels be inferred back to a condition descriptor,
- HE3: Can GPR be deployed at network level HFD surveys,
- HE4: Can window sampling be deployed at network level HFD surveys.

- **Application of findings and/or commercial output**

Key findings and often stand-alone packages related to condition evaluation elements (through Pavement Testing Services) were put to practise and evaluated through condition surveys in various road networks. Inventory collection and condition evaluation exercises were hence undertaken on the A50 and M77/GSO aiming to put elements of the Condition Assessment System proposed system into practice.

The developed Decision Support Toolkit was also evaluated in regards to ease of use and applicability. Inventory and condition data collected from field exercises were embedded in the developed toolkit and this was used to enable strategy generation and maintenance

planning. The alignment of objectives, research methods and research findings is diagrammatically presented in Figure 12.

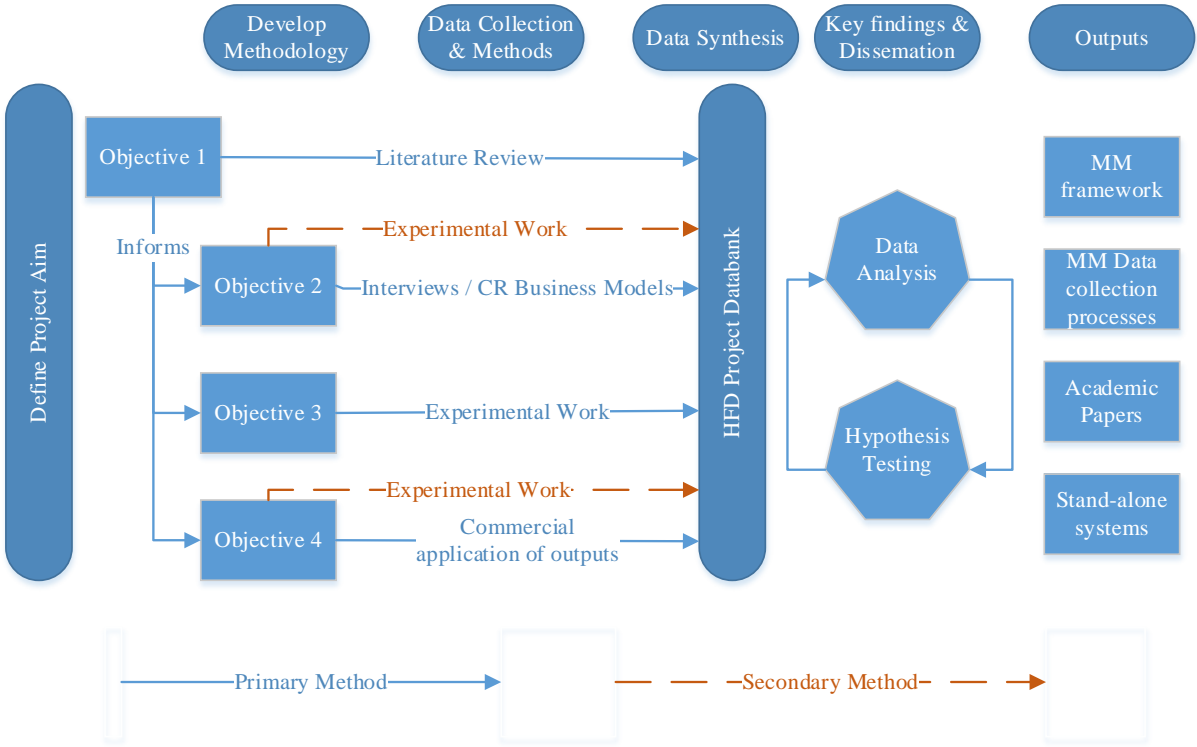


Figure 12 Research methods and approach to tackling the research aim

3.3 OVERVIEW OF RESEARCH TASKS

The following paragraphs provide an overview of the tasks developed through the four-year research work and how these relate to the main research objective. The overall task breakdown is structured around the requirement to approach Maintenance Management from both a top down (strategic, organisational focused) and a bottom up (engineered, technical oriented) routes in order to establish a management system and provide the means to develop a holistic data driven framework. The outputs thus address i) what data needs to be collected ii) how can this be achieved iii) how is the data to be used. Figure 13 depicts how individual tasks are aligned to research objectives

3.3.1 TASK 1A. EVALUATE AM STATE OF THE ART AND STATE OF PRACTICE

(INDUSTRIAL SPONSOR)

The first task enabled the RE to establish an introductory appreciation of Asset Management frameworks and explore drainage management in the UK roads network. The task was structured around a set of informal and open-ended discussions between the RE and the industrial sponsor's roads management team and participation in AM forums (Institute of Civil Engineering, CIRIA, Highways England). An exploratory evaluation of available literature pertaining to strategic management of roads assets, BSI ISOs and roads technical requirements established by the industrial sponsor was also undertaken alongside an in-depth assessment of pavement and ancillary assets proactive maintenance philosophies.

Outputs pertaining to Task 1a are expected to contribute to the probabilistic performance modelling approach of M77/GSO Highway network and the enhancement in sophistication of the deterministic regression analysis and investment prioritisation of other dTims (pavement investment planning decision support tool used by Connect) supported road networks across CR's roads portfolio. In the same manner, the rational applied to pavements links to drainage management and the establishment of the required methodologies for HFD investment planning.

3.3.2 TASK 1B –PROPOSE HFD STRATEGIC MANAGEMENT FRAMEWORK

Building upon the information generated from Task 1A, a strategic framework that would support the development the HFD Maintenance Management system was designed. This was aligned to CR's internal pavement management understanding and it defined all processes, information flows and routines to be embedded within the finalised MMS.

3.3.3 TASK 2 - EXPLORE HFD DESIGN, AGEING & RENEWAL PRINCIPLES (STATE OF PRACTISE & WITHIN SPONSOR)

Task 2 focused on formulating a clear overview of aspects of HFD design, deterioration mechanisms and renewal policies that could be embedded in an ageing / renewal model. This enabled the collection of information in regards to the current maintenance approach deployed throughout CR's road concessions, the contractual hand-back requirements and the available (to date) intervention options.

A comparison between DMRB propositions (service life, deterioration projection and gradual loss of asset function) and on-site serviceability levels and deterioration extent was achieved early on, enabling the RE to suggest the re-evaluation of initial design life projections to Highways England. By identifying HFD failure mechanisms an initial appreciation of loss of function was also formulated and some key outputs were taken forward and linked to Tasks 3-5.

3.3.4 TASK 3. CARRY OUT PRELIMINARY DESTRUCTIVE ON-SITE FIELD STUDIES

Task 3 introduced the experimental phase of the research work moving from the exploratory first year of the program (and Tasks 1,2) to site visits and condition and performance evaluation of in-service HFDs.

While the project focused initially on identifying gaps in HFD management literature and information requirements for a holistic system (Task 1) and applied maintenance thinking (Task 2) an exploratory evaluation of in-service HFDs across Connect's road concessions was planned and undertaken. HFD backfill samples were extracted from three road concessions (M77/GSO – Glasgow, A30/A35 – Exeter, A50 – Derby) for analysis. The selective sampling and sieving was structured in such a way as to enable the identification of the gradual

clogging mechanisms within a drainage trench and the varying fouling levels as a function of depth within the trench. HFD backfill was extracted in a layer by layer approach, geo-referenced and moved to Pavement Testing Services laboratories where the RE had the opportunity to carry out detailed sorting and fouling evaluation.

Through selective sampling and sieving an initial assessment of the physical condition of the aggregate was completed in various HFD locations / sites. This led to the formulation of means to quantify levels and extent of deterioration. The terms fouling and fouling index were devised and linked to the extent of sedimentation within a trench. Failure modes (top-down, bottom up) were further addressed by exploring the progression of fouling and this enabled the development of further performance and serviceability evaluation tasks linked to Task 4 and 5.

3.3.5 TASK 4. EVALUATE HFD SERVICEABILITY AND DEFINE ASSET SPECIFIC CONDITION METRICS AND FAILURE MODES

Task 4, enabled a differentiation to be made between physical condition (fouling levels and extent) and asset performance (which was related to serviceability and asset functions). The two are inevitably linked but also dissimilar; condition relates to the physical state of the asset and is a descriptor of asset information mapped to distress patterns and distress extent. Performance derives from condition and describes levels of service and the capacity at which the asset delivers its anticipated function (defined here as drainage capacity or drainability terms used throughout the work).

Task 4 drew from the preliminary condition surveys to evaluate levels of anticipated drainage capacity as a function of fouling extent through a laboratory based exercise. Hydraulic trials were conducted to study permeability levels with varying levels of fouling; this to produce a classification of HFD drainage performance (condition bands proposed ranging from Free

Drainage to Very Poor). A custom built large scale permeameter was designed at the Civil and Building Laboratories and used throughout the work in an attempt to use vertical permeability of the aggregate backfill as a performance descriptor. Controlled laboratory conditions enabled the RE to simulate in-service deteriorated conditions by artificially fouling Type B aggregate material to different degraded states.

The proposed fouling indices were examined in respect to drainage capacity; this enabled the 'fine-tuning' of discreet condition bands linked back to levels of fouling within an evaluated trench. Once the correlation between fouling indices (physical condition) and drainage capacity (performance) was completed along with the identification of failure modes (Task 3), discreet condition bands were proposed to inform follow up tasks related to modelling and ageing / renewal framework formulation.

3.3.6 TASK 5 – EVALUATE APPLICABILITY OF NDT&E TECHNOLOGIES FOR CONDITION ASSESSMENT

Through Tasks 2 to 4, assessment of physical condition and serviceability was completed employing a destructive and localised approach. Samples were extracted using plant & equipment and moved to a convenient laboratory environment to be further evaluated. Task 5 aimed at the evaluation of NDT&E technologies deployed in highway pavement and railway track-bed studies, identification of suitable tools and techniques for network level HFD assessment and laboratory experimentation to enable the transition to a NDT drainage specific protocol. This to establish a cost-efficient and HFD scale related condition assessment routine to be deployed across CR's road concessions.

Upon investigating NDT technologies in the roads and rail infrastructure a suitable tool (GPR) was selected and experimentation run through years 2 to 4. A broad literature review of GPR uses was developed and this lead to a HFD specific calibration methodology aimed at

identifying the appropriate type of radar and data processing routines to be followed. The investigation required both experimenting under controlled laboratory conditions (calibration) and conducting field studies (application). Sub tasks developed looked at:

- The extraction of dielectric properties, of clean moderately fouled and fouled sections (laboratory based);
- The study of how moisture affects the response of the GPR (laboratory based);
- The study of scattering analysis; data to study whether GPR response is sensitive to the scattering from void space in fresh HFD (laboratory based);
- The study of the Frequency domain based techniques for condition evaluation.
- The correlation of Field and Laboratory Data

Building on the previous task a framework that describes condition assessment using NDT&E (GPR) tools is to be formulated and used for future assessment surveys as part of the Condition Assessment Hierarchy. This links the developed fouling indices and condition discreet bands through performance considerations to standard GPR recognition patterns

3.3.7 TASK 6. ESTABLISH CONDITION ASSESSMENT SYSTEM

At best, HFD maintenance interventions are under the existing business model planned and undertaken based on visual cues derived from visual surveys carried out by road operators and maintenance crews. Often, empirical understanding of network drainage performance defines a time-based maintenance regime that is currently considered inefficient. A condition assessment framework is to be introduced based in a series of different tools that offer different advantages and/or disadvantages. Visual assessment (potentially through digitalized inspections in the future) can provide a fast and cost efficient method of condition appraisal of the asset. Rational ratings are to be developed and introduced in the management system to

quantify the physical condition of HFDs (proposed condition bands ranging from excellent to very poor).

Trial holes and sampling methods were examined throughout the work (Task 4). The lack of any information regarding current condition distributions of the asset across CR's roads network lead to extensive sampling and fouling quantification through sorting. Sieving and moisture content measurements were undertaken in collaboration with PTS in order to extract the information required to describe the extent of clogging in the trenches. The use of plant and machinery was proved early on a crude and inefficient approach to collect samples. The application of GPR on road surveys (Task 5) still required the use of calibration techniques (much like pavement assessment) and an alternative method to manual extraction of aggregate backfill was used in trial studies on Blythe Bridge By-pass (window sampling).

Central to the proactive management philosophy being developed through the EngD work, a condition assessment system that embodies the various evaluation technologies was structured. The CAS embeds condition evaluation elements that focus on visual surveys, selective sampling and machine-based surveys.

3.3.8 TASK 7: PROPOSE AGEING/RENEWAL RULES.

Parts of the early literature review (Task 1) focused on pavement deterioration prediction options mapped to CR's Asset Management systems. A HFD-specific ageing / renewal representation was thus proposed (through Task 7) to accommodate the requirement for asset condition prognosis. In principle a generalised deterioration model is usually employed by asset owners to project the asset's current condition in the future. This is often done by adopting a mathematical representation of deterioration rates and by taking into account the effect of maintenance options on the current condition of the asset. Ageing can be represented

using probabilistic or deterministic and regression based analysis depending on the type and range of condition data available.

Focusing on HFD deterioration understanding formulated through historic maintenance records, maintenance crew site experience, site visits and selective sampling and fouling quantification, a probabilistic network level deterioration model was developed to facilitate the requirement for condition prognosis. The model was based on Markov chains and probabilistic deterioration and drew from relevant pavement engineering literature to simulate asset ageing. Renewal rules were considered and formulated alongside treatment impacts (existing maintenance options include scarifying, replacing and the in-situ recycling). Renewal rules generally define when a treatment can be considered appropriate while impacts define the result of each maintenance option (ie does the condition return to a perfect 'score' once treatment is applied and how does the severity of distress change).

The markovian probabilistic approach offered a 'bird's eye view' of condition distribution across a road for a given HFD network and enables Connect to collate inventory and condition information and achieve maintenance planning according to investment requirements. This also enabled the representation of discreet condition distributions over a specified planning horizon at the network level while taking into account how the timing of different maintenance strategies has an effect on the projected condition distributions in a network.

3.3.9 TASK 8: DEFINE HFD DST TO INFORM MAINTENANCE DECISION MAKING

Combining the Asset Management thinking adopted through Tasks 1,2, the information needs and condition evaluation options and ageing renewal rules proposed (3-7) a DST system that overarches the proactive maintenance planning needs of CR was proposed aligned to the deteriorated characteristics of in-service HFD. The DST was structured with the purpose to

minimise investment requirements (constrained cost minimisation) linked to in-service constraints in its most basic form using Microsoft Excel. Connect will evaluate upon completion of the project if a transition to a proprietary pavement management system will take place.

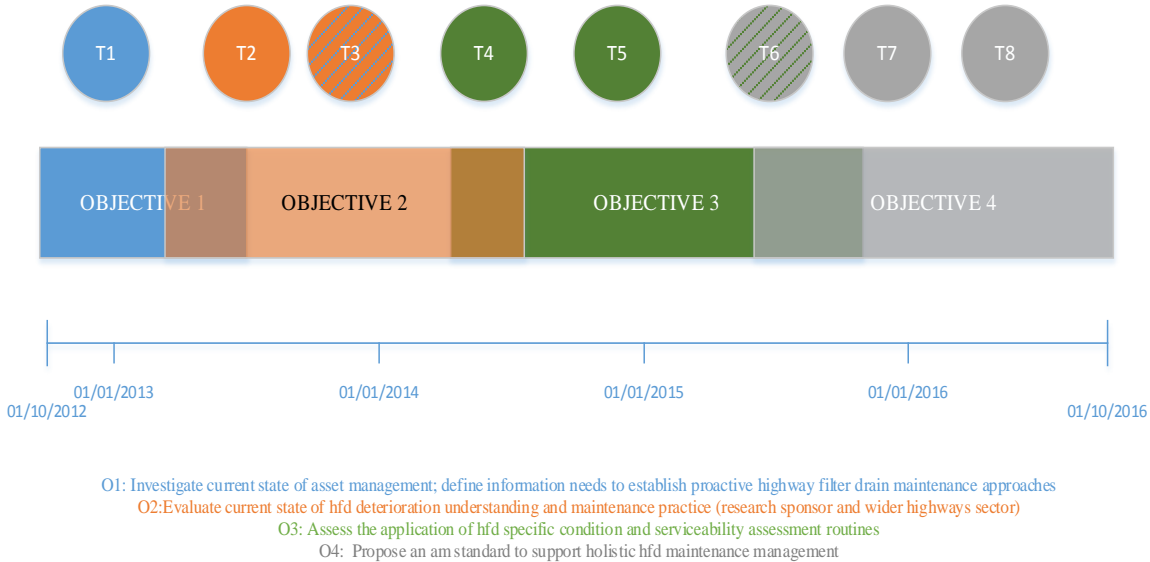


Figure 13 Alignment of Tasks and Objectives and general completion timeline

4 THE RESEARCH UNDERTAKEN

4.1 OVERVIEW

This chapter details the research work and key findings of the four-year EngD project. These are linked to the individual tasks as presented in Chapter 3 and describe the research novelty pertaining to the objectives established in Chapter 1.

The chapter is broken down in two sub-sections. Connect's Approach to Pavement Management is first discussed and then the breakdown of the proposed HFD Maintenance management system is presented. Both sections introduce work undertaken to establish the particular elements developed to reach a point where HFD maintenance planning can be embedded within a proactive system. Asset management theoretical and CR-specific frameworks are thus discussed and further developed. This enables the alignment of the proposed HFD management principles to Connect's business models.

4.2 CONNECT'S APPROACH TO PAVEMENT MANAGEMENT

This part of the study focuses on identifying and evaluating the Asset Management thinking and highway / pavement related systems embedded within the spectrum of CR's Life-Cycle planning across their 5 PFI concessions. The anticipated outcome (identified by Task I) is establishing the means to lay the foundations for the HFD maintenance management system by drawing parallels between pre-existing systems and new information and processes requirements. Such an approach will enable a swifter and smoother transition to a proactive maintenance and investment planning system specifically designed and implemented for the aforementioned drainage element.

In practice and from Connect's perspective, Pavement Management is central to developing, updating and coordinating all activities related to maintaining and rehabilitating pavement and

ancillary assets. The whole system is structured around AM principles that define the what's and how's required to achieve a proactive, systematic and engineered management of tangible assets. CR's PMS is structured around in-service and handback performance requirements (which depict anticipated and agreeable levels of service in a given highway network).

Typical tasks and routines associated with the care of assets generally include:

- Inventory of physical assets to include structural characteristics
- Inventory of past maintenance work
- Condition surveys targeting pavement / structures serviceability, safety and structural capacity
- Pavement analysis (condition distribution, deterioration modelling)
- Performance monitoring mapped against key contractual performance indicators
- Investment Analysis, prioritisation and what-if scenarios to formulate maintenance budgets

Connect's annual updates of Life Cycle and AM plans are formulated upon collection and evaluation of condition data pertaining to pavement networks, structures, drainage and ancillary assets. There are different levels of sophistication embedded in each asset - specific DST and there is still work undergoing aiming the development of an all-encompassing highway asset management decision support tool. The Whole Life Plan cycle for pavements can be broken down in tasks listed below:

- Condition Data Collection & Processing
 - SCANNER / TRACS (pavement serviceability)
 - SCRIM (skidding resistance / safety)
 - Deflectograph (structural capacity)
 - Ground Penetrating Radar / coring (other ad-hoc surveys, if / when required)
- Updating DST inventory and condition database

- Updating DST model variables (if and when required)
- Strategy Optimisation (constrained cost minimisation / maximised investment benefit constrained budgets) using proprietary DST IT system
- Preliminary Programs (network and project level)
- DBFO-specific investment committees (project level 2 year project selection)
- Updating pavement DST models and final annual maintenance programs.

The process is broken down and visualised in Figure 15. Investment committees are CR's internal mechanism which was set in place to achieve the alignment of AM objectives and operational output; this in practise institutes a clear line of sight between the strategic side of asset management (client / stake and shareholder expectations, contractual requirements) and the tactical / engineered end of the equation (scheme planning and project delivery).

The annual condition-data collection cycles follow the contractual serviceability/safety and structural capacity requirements as defined in concession specific Operation and Maintenance contracts. These suggest the core asset-condition data to be collected, the data collection intervals and the performance targets pertaining to in service and hand-back requirements for each asset class. Pavement and condition information for the three Highways England concessions (A30/A35 DBFO, A50 DBFO, M1A1 DBFO) and Carlisle Northern Development Route (CNDR) DBFO, are imported into a proprietary database linked to Deighton's Total Infrastructure Management System (dTims). dTims enables the formulation of decision trees, treatment rules, treatment impacts and investment strategies upon optimisation of investment requirements.

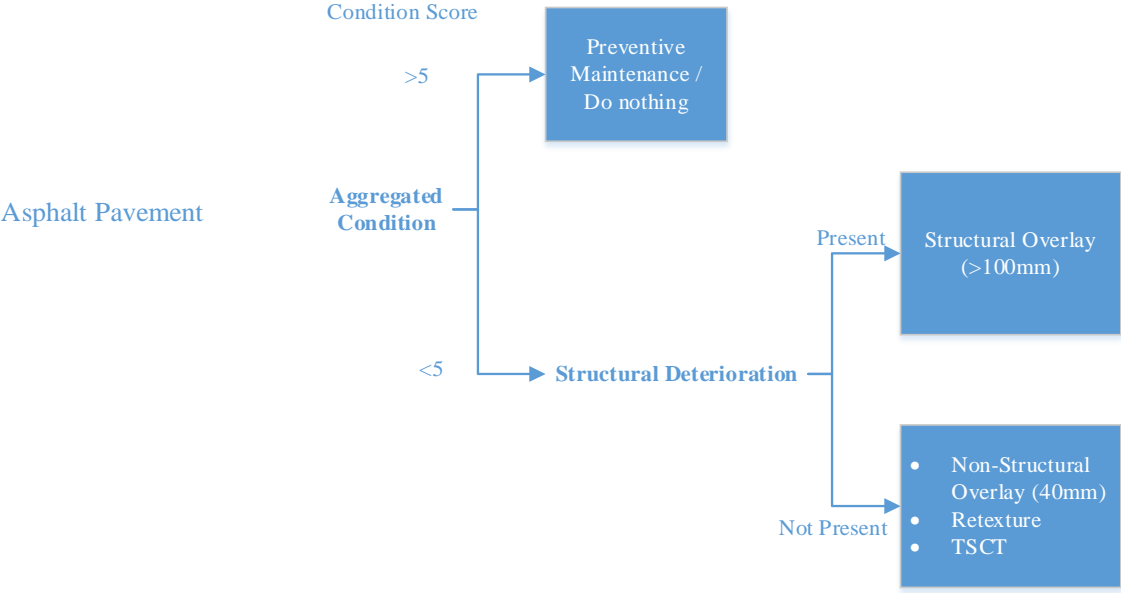


Figure 14 Simplified Decision Tree for asphalt pavement section

Deterioration models and deterioration projection is carried out externally by focusing on each key condition variable and carrying out regression analysis using historical data; deterioration trends then enable predictive capabilities for each condition index to be generated and embedded within models in the form of linear equations. CR does not adopt any particular mechanistic or empirical methodologies to forecast pavement deterioration. Instead, the annual output of Traffic Speed condition surveys is used as the backbone of condition modelling on a variable-by-variable basis. The DST base table includes inventory information and network sectioning for all pavement assets across each concession. Key information typically stored within the database include type of pavement (Long or Non-Long Life), numbers of lanes, HAPMS referencing, and surfacing material (HRA, SMA, other proprietary surface dressing material). This type of information was generated once and is typically steady with updates focusing on newly constructed sections, which take place rarely in DBFO projects.

DST engineering rules encompass all condition and performance related components of the existing PMS. Here, treatment rules, triggers and impacts are defined and condition forecasting and condition breakdown models are developed and then adopted. Pavement

performance models for different pavement types (in regards to surfacing options), carriageway lanes and geographic locations (environmental and traffic conditions) are hence developed and linked to dTims' model variables. Strategy optimisation can then be achieved by defining in-service performance constraints and asset-specific hand-back requirements. Such constraints are typically representative of the worst acceptable condition a pavement section can be at any point through its projected service life. KPI's are hence formulated for structural capacity and safety related performance variables of all pavement sections within a given network. Failing to comply with such performance requirements yields penalties which can in some be in the form of large financial deductions. With DBFO contracts, performance requirements are usually rigidly defined. Different and quantifiable metrics for pavement rutting, texture depth and structural residual life at handback are for example provided in any given O&M contract (in essence data to be assessed and data collection processes are well established well understood and well followed). Optimisation thus takes the form of constrained maintenance cost minimisation – a typical option for any and all pavement management IT systems available in the sector.

Typical dTims outputs include annual proposed project level schemes, forecasted network level condition breakdown under the selected and optimised strategy, and hence overall network level investment requirements. Project selection and subsequent annual programmes are then developed through concession specific investment committees where the output of dTims modelling and generated scheme list is mapped to on-site conditions, scheme selection practicalities and maintenance requirements as proposed by MAC operator pertaining to all other ancillary assets and structures for which condition is usually not measured but rated. Through these committees, maintenance budgets are generated to also include allocations for HFDs and are thus central to the development of all elements coupled to the maintenance management system proposed in the following sections.

Highway Filter Drains Maintenance Management

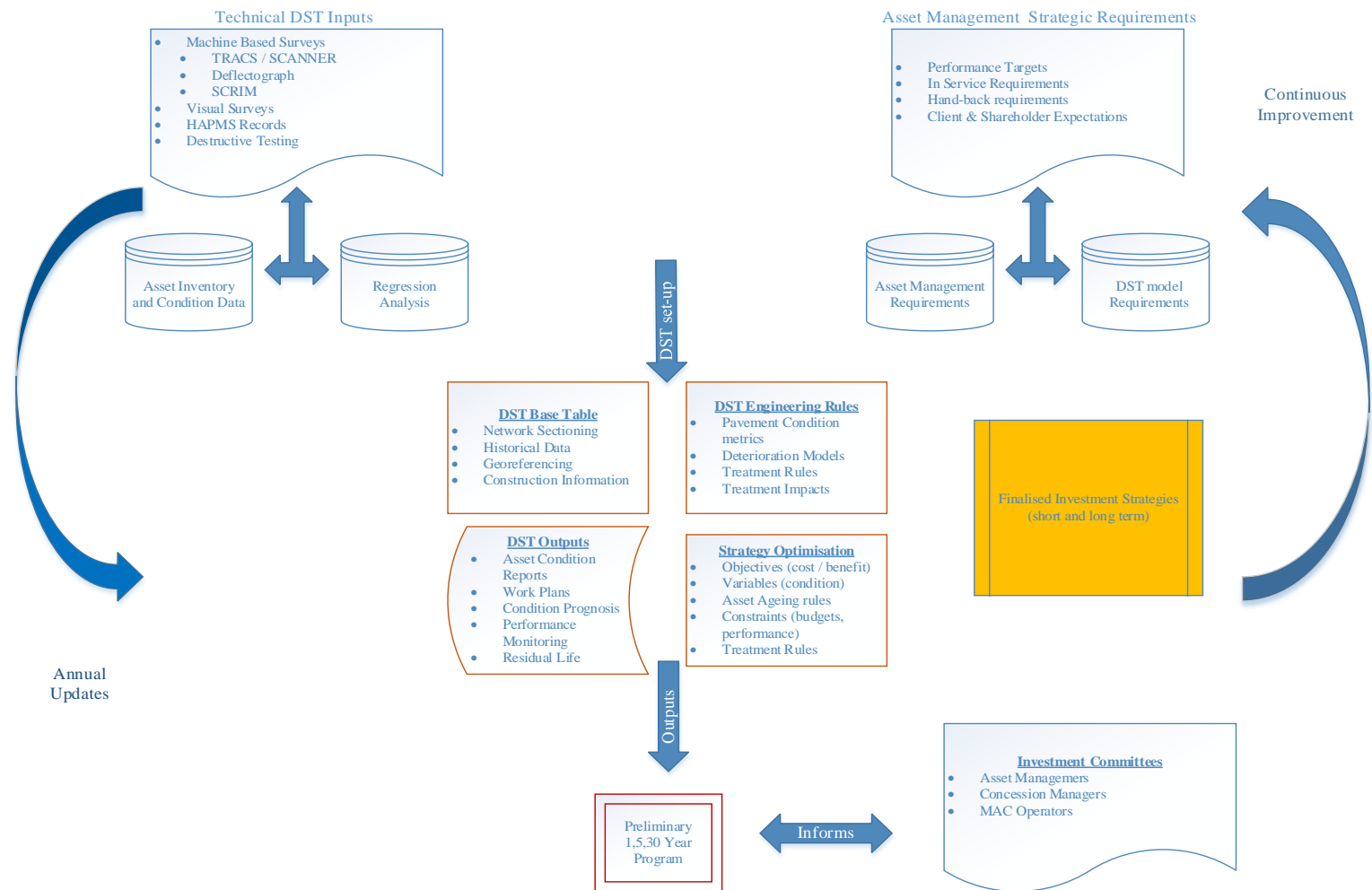


Figure 15 Connect Roads approach to PMS

The M77/GSO DBFO posed a number of unique challenges in the formulation and optimisation of WLPs and investment strategies. Due to limited available condition data and pavement deterioration that failed to be represented by typical regression equations, a maintenance planning approach driven by visual assessment and transition probability matrices was defined as a course of action in recent years. The approach tackled the ongoing issue of out-of sync machine-based data and actual on-site conditions but failed to capture condition projection in a systemised and engineered manner. As part of the project deliverables and in line with **Tasks 1b** and **8** (see **Section 3.3**) a probabilistic condition projection methodology and a pavement DST was built to support proactive maintenance planning. This would enable the development of short-to medium term investment strategies and also lay the foundation for the development of the HFD proactive maintenance system.

The whole process integrating inventory data, visual condition information, discrete condition bands, DST set up and typical outputs is presented in Figure 16. Five condition grades were used to assess pavement condition ranging from Very Good to Very Poor [VG, G, F, P, VP]. A visual assessment was undertaken in 2016 and a base condition array displaying the condition distribution across the M77 route was hence developed. Deterioration was then projected by adopting a Markovian Transition Probability matrix for each surfacing type found in the network (currently SMA, HRA). Transition probabilities were defined based on engineering judgement and prior network knowledge and anticipated service life of surfacing material options. The TPM for HRA surfacing material adopting a service life $n = 16$ years and linear deterioration was thus calculated as shown below:

$$P = \begin{bmatrix} p_{11} & p_{12} & \dots & p_{1n} \\ p_{21} & p_{22} & \dots & p_{2n} \\ \vdots & \dots & \ddots & \vdots \\ p_{n1} & p_{n2} & \dots & p_{nn} \end{bmatrix} = \begin{matrix} VG \\ G \\ F \\ P \\ VP \end{matrix} \begin{bmatrix} 0.765 & 0.235 & 0 & 0 & 0 & 0 \\ 0 & 0.765 & 0.235 & 0 & 0 & 0 \\ 0 & 0 & 0.765 & 0.235 & 0 & 0 \\ 0 & 0 & 0 & 0.765 & 0.235 & 0 \\ 0 & 0 & 0 & 0 & 0.765 & 0.235 \end{bmatrix}$$

Since the DST aims at identifying major resurfacing investment requirements, two maintenance options are used (40mm HRA or SMA) assuming like-for-like interventions (ie replacement of SMA surfacing with SMA surfacing) and maintenance costs are extracted from the DBFO management accounts and discounted to match average 2007 prices. To simulate the effect of maintenance treatments a generalised deterioration / renewal mathematical model (conceptualised by De La Garza and Krueger (2007)) is used as presented in the equation that follows:

$$\begin{aligned}
 & \text{Condition}_j(t + 1) \\
 &= \text{Condition}_j(t) - \frac{\text{Condition}_j(t)}{D_{jk}} + \frac{\text{Condition}_i(t)}{D_{ij}} + \sum R_{kj}(t) \\
 & - \sum R_{ji}(t)
 \end{aligned}$$

In principle, the equation determines the annual change of the asset condition by calculating the effects of maintenance treatments on the various condition levels and then ageing the resulting condition distributions according to the adopted deterioration rates. Deterioration rates (denoted by D_{ij} and D_{jk}) were based on the TPM for each surfacing material, while R_{kj} and R_{ji} denote the upstream condition changes due to maintenance interventions (i.e. the impact of maintenance on current condition). In this case the two maintenance options reset a deteriorated section to a Very Good / as new condition. All this has been embedded and structured in the excel based toolkit to monitor and follow deterioration and project and output network level performance and maintenance needs.

Outputs related to the excel based DST developed for CR include an annual maintenance spend tracker, network level performance breakdown for SMA / HRA wearing courses and annual treatment lengths for each surfacing material used in the concession. The tool-kit has

been communicated with Transport Scotland and will be central for maintenance planning purposes to supplement dTims optimisation and analysis for the following years.

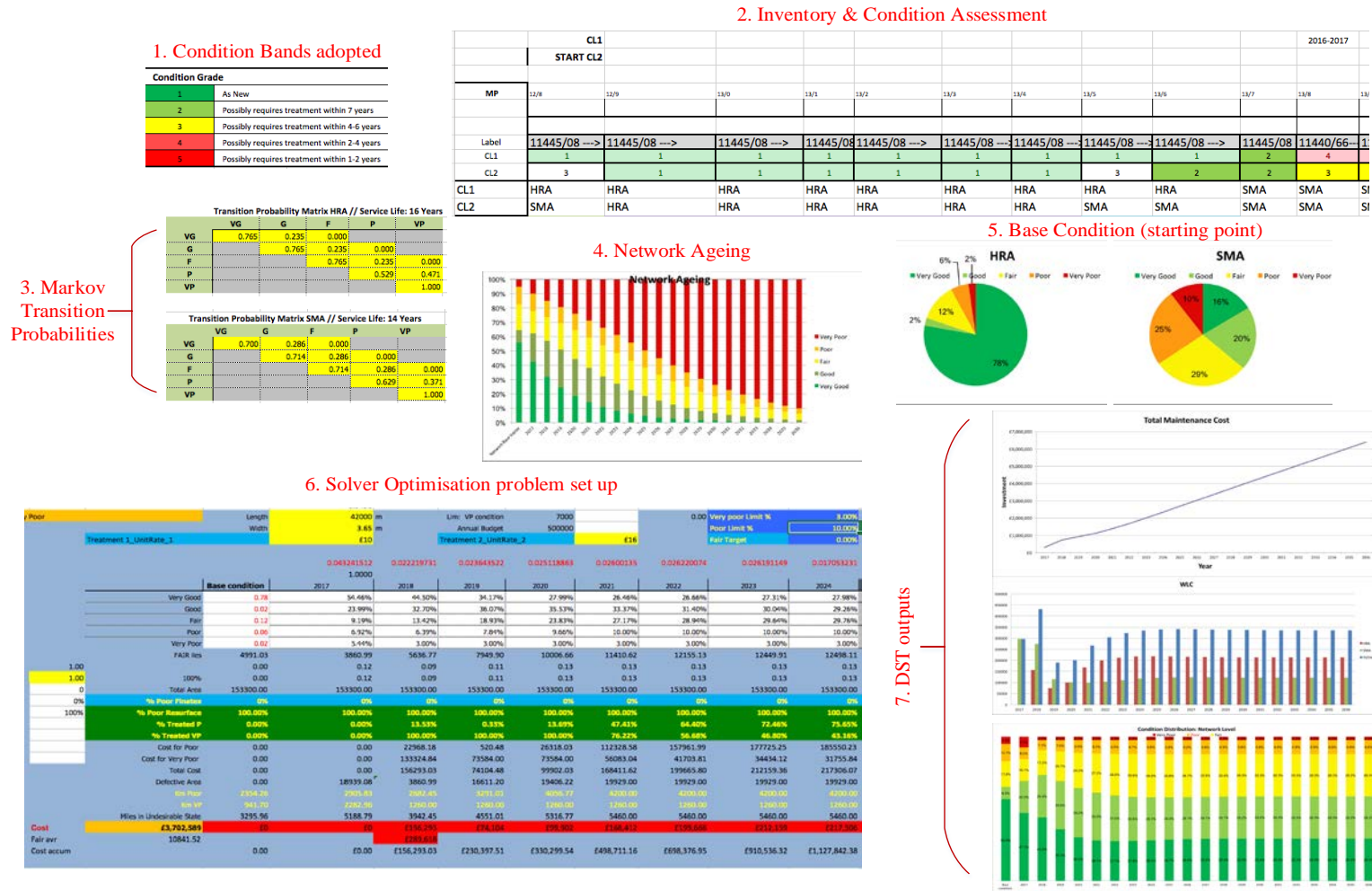


Figure 16 Formulation of pavement DST for M77/GSO DBFO. Figure includes TPM adopted, visual survey data, and optimisation routine in excel software

4.3 DEFINING A HFD MM APPROACH

4.3.1 OVERVIEW

This section presents how by building upon the information generated in the Current Practise section linked to Connect's approach in maintenance planning, the HFD-specific management system was formulated to be used by CR in the annual internal WLP processes. Key supporting components / processes, data requirements and information streams that will enable the formulation of a HFD Management strategy are identified developed and embedded within the proposed system.

Asset specific MS are essentially the collection of all tools, technologies and processes that help managers make better decisions and manage their assets more effectively. While such systems are adopted and fine-tuned for different asset groups within the highway network, they integrate at their core the same systems thinking and management principles (this work emphasises how drainage management has not yet embedded such an approach in this particular scenario). They are fundamentally information driven, heavily dependent on databases (inventory, condition, historic maintenance, budgets, M,R&R options/impacts/costs) and employ a particular type of analysis that allows asset managers to fine-tune interventions, optimise asset life cycles and carry out investment decisions for preservation, expansion and operation of any given network. The data required for a MS are produced by monitoring and inventory activities, while modelling provides the tools for planning, trade-off analysis, ranking, and optimisation.

Upon establishing the goal of the MM framework to be built (linked to the project aim – see **Section 1**), the operations listed below were generated to tackle the gaps in the current state of practice in line with any generic MS layout. These are linked to HFD asset information

generated by evaluating serviceability requirements, deterioration understanding, maintenance options and handback criteria. The following sections address three main questions; what assets, what condition and what needs be done.

- Evaluate 'base' asset data and inventory
- Establish means to assess condition and levels of service (diagnosis)
- Propose means to project condition and levels of service (prognosis)
- Evaluate HFD maintenance options and maintenance triggers and impacts
- Build HFD ageing / renewal rules
- Propose HFD maintenance DST

Each task and component is discussed in the subsequent sections.

4.3.2 STRATEGIC PLANNING

A strategic map was formulated for the purpose of introducing the systemised HFD management approach and communicated internally to CR. Elements and work-packages of this are described in the Research Tasks section and from these outputs are linked to the plan. The strategy synthesized key actions and information sources needed to achieve such goals and all critical elements and routines to be developed throughout the four-year project for the implementation – seen in Figure 17. In essence, the strategic plan is comprised from four main types of inputs, processes or information streams. These are either related to identifying data inputs and processes required, techniques to enable the collection of the relevant data and finally the tasks to process and evaluate the data to generate value adding information. Paper 2 (Appendix B) aims to communicate the prerequisites for a HFD specific maintenance management system by identifying information types, information streams and knowledge generated by an all-encompassing framework. The same paper also discusses how such

information can be acquired looking at the engineering end of the AM equation; this focuses on the application of the proposed strategy, what kind of data are to be collected, how are these to be acquired and used and in what sense will the outputs reinforce the case of AM and be of true value.

Key milestones for the completion of the system include:

- Build network referenced inventory database

Component that stores information about the drainage asset in respect to location (network breakdown), construction (depth, length, materials used). An evaluation of information requirements at the network and project level lead to assessment of inventory collection and database building options. Inventory data were thus collated from as-built drawings (to some extent), past maintenance records and network walkovers. Upon establishing how inventory could be built (what to include) an inventory exercise was carried out selectively across CR's road concessions.

- Determine feasible maintenance options

Component that relates to identifying current maintenance options and applicability according to asset's current condition. Financial considerations were also factorised by liaising with DBFO MAC operators and evaluating outrun costs through investment committees. Condition driven maintenance, was established by developing and using the proposed condition metrics that tied to modelling techniques and deterioration projection.

- Build Condition Assessment Component.

Condition assessment system to enable condition data collection and classification of deficiencies accountable for drainability levels. This was formulated upon adopting and applying condition evaluation techniques based on a combination of destructive, non-destructive and visual assessment methods

Overall, the plan can be broken down in four main sub-elements, which are detailed in the follow up sections. These are:

- Inventory Collection Components
- Condition Diagnosis Components
- Condition Prognosis Components
- HFD DST Component

The information generated from each sub - element eventually feeds into the HFD decision support tool, which will be the basis for developing and introducing proactive maintenance planning for the drainage asset.

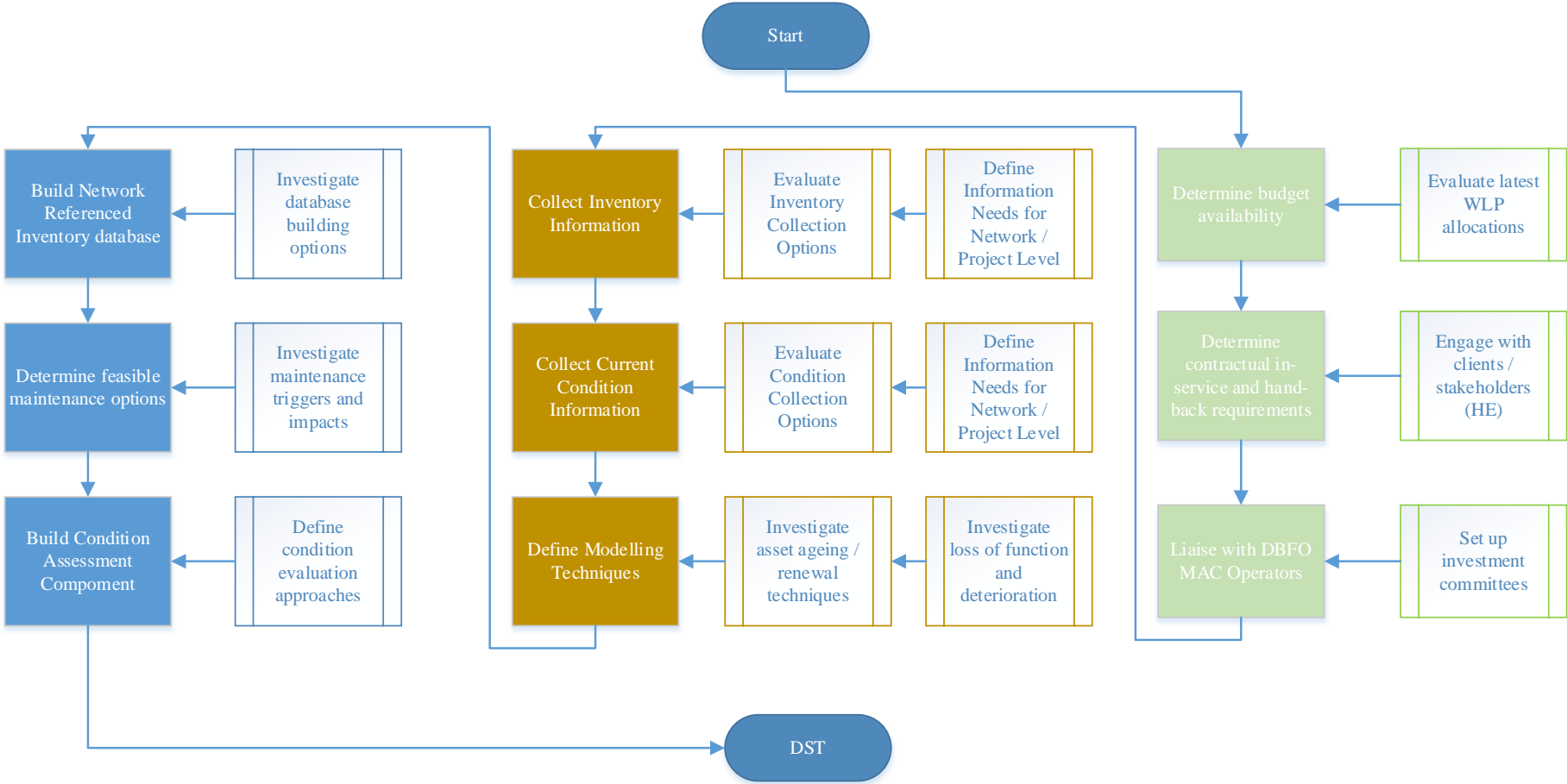


Figure 17 Schematic Representing strategic planning for HFD maintenance management

4.3.3 INVENTORY OPERATIONS

Network-level inventory data collection exercises were carried out for HFDs found on the A50 DBFO network. A preliminary desk study, an evaluation of as-built data and network walkovers were undertaken to enable collation of enough data to build a representative HFD database for this concession. The primary focus of the exercise was to establish a database to provide information in regards to:

- Total length of HFDs found in network
- HFD location referencing aligned to A50 road links / sections
- Construction materials used
- HFD sections age

Parts of the A50 DBFO (Blythe bridge by-pass, Sudbury) were constructed between 1970 and 1975 and inventory evaluation using as-built drawings lead to no significant outcomes. While data has been collated to represent total lengths of HFD across such sections, the objective of identifying HFD construction materials was not fully met as CR held no official records of construction materials used. Further construction information was generated from sampling and sieving, presented in following sections.

In total approximately 64km of HFD trenches have been built across the DBFO network. Without full records it was assumed that the average depth of trenches is 1m and the width of each trench is approximated to be 0.7m. A breakdown of the inventory collected from the exercise can be seen in Table 2. This information is adopted in follow-up sections and the DST development operations.

Link No	Location	HFD length (m)	Material Grading	Opened to Traffic
1	Blythe Bridge bypass west	1331	/	1975
2	Blythe Bridge bypass east	1944	/	1975
3a	Blythe Bridge to Uttoxeter (1)	3319	/	1985
3b	Blythe Bridge to Uttoxeter (2)	26183	/	1985
4	Uttoxeter to A518 (new)	410	Type B	1998
5	A518 to Marrston La. (new)	417	Type B	1998
6	Marston Lane to A515 (new)	245	Type B	1998
7a	Subury (new)	-	/	1970
7c	Sudbury Roundabout	301	/	1970
8a	Sudbury to Foston Prison Access	31	Type B	1995
8b	Foston Prison to A511	-	Type B	1995
9a	A511 Slip to Slip	41	Type B	1995
10a	A516 Slip Road to Slip Road	647	Type B	1997
10b	A516 to A38	4357	Type B	1997
11	A38 to A514	14948	Type B	1997
12	A514 to Derby Spur	9206	Type B	1997
13	Derby Spur to B6540	650	Type B	1997
14	Derby Spur Road	1614	Type B	1997

Table 2 Network Level Inventory Data to build A50 DBFO HFD database

4.3.4 CONDITION DIAGNOSIS

With conventional HFD condition assessment thinking (and lacking any official evaluation framework) data for condition evaluation could be obtained from predetermined test sections or through visual inspections when the research work commenced. Both means would fail to address fouling levels and fouling extent and deterioration in a quantitative manner. The former option will inevitably enable only discrete data evaluation (for an asset that usually spans over many kilometres), or costly and time demanding sample collection and sieving / sorting. The latter is based on rating rather than measuring, and no guide exists to control subjectivity in the measuring process. Machine-based condition data collection hasn't yet been implemented even though a wide range of GPR libraries linking material properties of pavement systems or of assets that bear similarities to HFD backfill do exist and suggest there can be a possible way forward.

In truth, a fully comprehensive inspection of long-spanning drains is neither practical nor financially viable in a dynamic highway network. An hierarchical assessment system of condition surveys will eventually include some or all of the aforementioned assessment techniques varying in frequency and Lifecycle planning added value. The merits of adopting a condition based approach embedding machine based data and how that can be integrated with a maintenance management system are described in Paper 2 – Appendix B.

The following sections present all the research output related to HFD condition evaluation; a visual assessment methodology is defined, means to destructively assess and characterise drain samples are proposed and then applied to site conditions and finally non-destructive laboratory and in-situ characterisation of HFD material is carried out.

4.3.4.1 Visual Assessment

A visual assessment survey is a quick and generally inexpensive approach to assess the condition of linear highway assets and can be undertaken in-house by the MAC Operator in each road concessions on an annual basis. To minimise inspector bias, a guide to support data collection on-site was generated to also be integrated in the general Condition Assessment System that underpins the maintenance decision support tool.

The internal assessment standard was produced by evaluating network experience and extrapolating the site team's understanding of asset deterioration also factorising preliminary field studies at the M77/GSO and A30/A35 DBFO. With two particular failure modes identified (surface crusting or top down and bottom up failure) and progressive drop of performance with fouling building-up in the trench, four main performance tiers have been defined to visually assess condition. These are: Excellent Condition, Fair Condition, Poor Condition and Very Poor. Two additional condition tiers are embedded in the HFD grading system to represent the crusting failure (Fair Crusting, Poor Crusting). Table 3 breaks down

the different condition bands also presenting anticipated performance and proposed action for HFD section as a function of the condition grade identified at the survey.

Highway Filter Drains Maintenance Management

Grade	Excellent Condition	Fair Condition	Poor Condition	Very Poor Condition	Fair Crusted	Poor Crusted
						
Overall Asset Condition	As new	Superficial defects, no obvious fouling	Moderate to high level of fouling, parts of backfill at surface sometimes not visible	Extremely high fouling levels, aggregate material not visible at surface of trench	Localised vegetation growth, low fouling levels	Moderate to high fouling levels, aggregate material not visible at surface of trench, extensive vegetation growth
Anticipated Performance	As new	No obvious drop	Dropped; material permeable but performance reaching critically low levels	Practically impermeable	Main body acceptable, surface water removal reduced	Practically impermeable
Risk of Failure	None	None	Medium	Extremely High	Medium	Extremely High
Action	N/A	N/A	Monitor, further testing	Full reconstruction	Identify for scarifying	HFD cleaning and aggregate top-up

Table 3 Condition Grades, anticipated performance and proposed actions based on HFD visual assessment system

4.3.4.2 Destructive Testing

A series of field evaluation studies have been conducted throughout the period of the four year project targeting in situ classification of HFD aggregate material. Samples have been collected from A30/A35, A50 and M77/GSO DBFOs, transferred to PTS and/or Loughborough University soil laboratory and evaluated to quantify and evaluate the fouling levels and of in-service drains. Subsequently the focus was shifted on methodologies that would enable the introduction of a distress quantification index in a way that the anticipated drop of serviceability (drainage capacity) can be measured and rationalised in an engineered way.

4.3.4.2.1 A30/A35 DBFO sampling

Five locations across the A30/A35 network (160 route-kms) ranging in condition (in terms of visual cues) were selected for initial investigation (see Table 4). Trial holes were dug out and samples were collected, stored and transported to soil laboratories for further evaluation. To test fouling propagation within trenches and examine progressive deterioration aggregate samples from two locations (Axminster) were collected in two ‘batches’; about 600mm depth of material is removed split in upper and lower parts and stored in water-proof containers to withhold moisture content.

Visual assessment of the identified drainage sites showed a wide range of condition distributions across the HFD sections under evaluation. The surface condition of trenches found in Axminster (Axm A and Axm B) was generally acceptable suggesting high levels of anticipated drainage capacity. In contrast, filter drain material from sites at Eype, Bridport, Charmouth Roundabout and Dorchester Bypass exhibit signs of advanced deterioration, surface crusting and excessive vegetation growth (Table 4).

Sieving of the extracted samples enabled the identification of failure modes and fouling levels and composition. To establish (in qualitative means initially) the extent of deterioration a comparison between sample particle size distribution curves and HFD backfill requirements can be seen in Table 5. As a general remark, with the exception of samples Axm B1, Axm B2 all samples fail the gradation requirements of either Type A or Type B material specifications with deteriorated samples generally suggesting that Type B material was used for backfilling trenches.

Location	Comments	Visual Condition	Treated
Axminster Bypass A	No crusting, no vegetation	Fair	No
Axminster Bypass B	No crusting limited vegetation growth	Fair	No
Eype	Excessive crusting and vegetation present	Very Poor	Yes
Bridport	Excessive crusting and vegetation present	Very Poor	Yes
Charmouth Roundabout	Excessive crusting and vegetation present	Very Poor	Yes
Dorchester Bypass	Excessive crusting and vegetation present	Very Poor	Yes

Table 4 Visual Assessment of 6 sites selected for sampling & sample extraction

The comparison of samples Axm A1 and Axm A2 and Axm B1 and Axm B2 indicates increased fouling levels with increased depths. In fact, five sites generally exhibit signs of bottom-up failure progression. The sedimentation of the four failed sections at lower parts of the trench suggests that cleaning the uppermost volumes of material (scarifying) will result to low benefit in terms of asset performance and longevity. In reality, the assessed sections are part of drainage systems constructed between 20 and 30 years ago. Scarifying or other techniques targeting the uppermost of the trench are thus anticipated to have limited to no effect and full reconstruction would be a more effective long-term solution.

By taking into account general drainage capacity requirements, past flooding events in the vicinity of the evaluated linear drains and the extensive fouling of the remaining 4 sites deep aggregate replacement was undertaken to replace the fouled material.

Table 5 Trial Holes A30/A35

Location	Material Passing Sieve Size														
	63 mm	40 mm	31.5 mm	20 mm	16 mm	14 mm	10 mm	6.3 mm	4 mm	2 mm	1 mm	0.5 mm	0.25 mm	0.125 mm	0.063 mm
Type A		100%		80-99%			50-90%		30-75%	15-60%		0-35%	0-4%		0-3%
Type B		80-99%		0-20%			0-5%								
A30/A35 DBFO															
Axm A1	100%	100%	65%	26%	19%	15%	12%	10%	9%	8%	6%	4%	3%	2%	1.1%
Axm A2	100%	100%	90%	31%	21%	19%	16%	14%	13%	11%	10%	8%	6%	4%	2.6%
Axm B1	100%	99%	70%	11%	6%	5%	4%	3%	3%	3%	3%	2%	1%	1%	0.4%
Axm B2	100%	97%	60%	8%	5%	5%	5%	5%	5%	5%	4%	4%	3%	2%	1.1%
Eype	100%	100%	86%	37%	25%	22%	21%	21%	20%	19%	17%	14%	10%	7%	4.7%
Bridport	100%	100%	99%	61%	42%	37%	33%	32%	31%	30%	29%	27%	25%	24%	22.9%
Dorchester Rb	100%	92%	95%	61%	42%	37%	33%	32%	31%	30%	29%	27%	25%	24%	22.9%
Charmouth Rb	100%	100%	77%	48%	38%	37%	35%	32%	31%	31%	29%	27%	24%	19%	15.9%

4.3.4.2.2 M77/GSO DBFO

The drains in this study were constructed between 2003 and 2005 and have been in service for approximately 10 years. In this period, a number of localised HFD failures have been reported across the M77/GSO network and remedial work focused in surface scarifying and removing excess surface vegetation. A typical HFD section on this network is constructed using Type B aggregate as the main drainage body; top up material comprises of aggregate of 70mm nominal size. As-built drawings indicate that geotextiles were used during construction to separate the top-up material from the main body.

A visual survey was undertaken on the network prior to any destructive sampling taking place to establish an initial understanding of the condition breakdown of HFDs across the road. Trial holes were dug on the carriageway verge at five locations (trial holes A to E) and material was removed layer by layer (approximately 300mm per layer, up to a predefined depth of 1m). At two locations (C and D), the excavation depth reached a geo-fabric located 1m deep in the drain.

Unlike HFDs on the A30/A35 network, drains across the M77/GSO were generally functioning at acceptable levels of service. Particle size distribution curves indicate deteriorating sections but that is expected as HFDs here were in operation for over a decade and the first main cycle of maintenance and renewal strategies is expected to be fast approaching.



Figure 18 HFD trial M77D on pavement verge M77 and dug out material (exhibiting low levels of fouling)

Top up material used in HFDs was contractually specified for application in the road concession in a way similar to Type B aggregate backfill. Samples M77A1, M77B1, M77C1, M77D1 and M77E1 correspond to the uppermost 300mm from each evaluated location. Comparisons between current fouled states and material gradation thresholds can be made in Table 6. At two sampling sites (Location A and location B) fouling concentrations (sediment particle matrix smaller than 10mm nominal size) are found to be lower in the sample batch collected below the trench top up suggesting a top down failure (crusting and vegetation growth limited at the uppermost of the HFD trench). Such a failure mode can be tackled with surface cleaning and rehabilitation techniques targeting renewal of the top-up material.

Deeper sections in all other locations exhibit higher sedimentation levels than the top-up material. For these locations a drop of serviceability / drainage capacity cannot be linked with surface crusting or any failure mode in line with a top down sedimentation. Subsequently any effort to remedy the loss of performance would require a type of intervention that would renew the initial void space of the ‘basal’ parts of the trench. Table 6 tabulates the results; samples from trial hole locations C and E fail (as-new) gradation requirements with sediment concentration levels being between 4 and 12 times higher than the proposed new-built

requirements. Samples from location C presenting fines content of 27% and 60% 600mm and 900mm deep in the trench respectively are also expected to fail performance requirements as the aggregate particle matrix is largely fouling dominated. These locations are monitored and future maintenance planning will take such observations into account.



Figure 19 Samples from M77/GSO sieving exercise; oversized aggregate can be observed in B1 sample (top up) moderately fouled Type B material on B3

Highway Filter Drains Maintenance Management

Table 6 Sampling and sieving data for M77/GSO HFD sites

Sample / Sieve Size	63 mm	40 mm	31.5 mm	20 mm	16 mm	14 mm	10 mm	6.3 mm	4 mm	2 mm	1 mm	0.5 mm	0.25 mm	0.125 mm	0.063 mm
Top-Up	50-100%		0-20%			0-5%									
Type B	80-99%		0-20%			0-5%									
M77A1	81%	55%	44%	32%	30%	29%	27%	25%	23%	20%	17%	14%	10%	6%	3.4%
M77A3	77%	33 %	26%	13%	11%	10%	8%	6%	5%	4%	3%	3%	2%	1%	0.7%
M77B1	87%	48%	39%	28%	25%	25%	23%	21%	20%	18%	15%	12%	9%	5%	3.3%
M77B3	95%	81%	55%	28%	24%	20%	13%	11%	10%	9%	8%	7%	7%	6%	5.5%
M77C1	97%	55%	44%	32%	30%	29%	27%	25%	23%	20%	17%	14%	10%	6%	3.4%
M77C2	96%	62%	44%	32%	30%	29%	27%	25%	23%	20%	17%	14%	12%	9%	7.3%
M77C3	91%	62%	76%	67%	65%	63%	60%	55%	51%	46%	40%	34%	29%	24%	19.5%
M77C4	77%	74%	67%	38%	30%	27%	21%	17%	13%	10%	8%	6%	4%	3%	2%
M77D1	33%	24%	20%	15%	14%	13%	12%	11%	10%	9%	7%	6%	4%	3%	1.6%
M77D2	85%	47%	34%	22%	20%	19%	16%	14%	12%	10%	8%	6%	5%	4%	2.9%
M77D3	94%	65%	53%	43%	38%	37%	34%	30%	27%	23%	19%	16%	13%	11%	8.3%
M77D4	96%	90%	70%	25%	19%	17%	15%	14%	12%	11%	9%	8%	7%	6%	5%
M77E1	67%	43%	33%	27%	24%	23%	21%	18%	16%	13%	11%	9%	7%	5%	3.7%
M77E2	100%	91%	61%	17%	13%	13%	11%	10%	9%	9%	8%	7%	6%	5%	3.8%
M77E3	100%	58%	55%	38%	34%	32%	29%	26%	22%	19%	16%	13%	11%	9%	7.6%

4.3.4.2.3 A50 DBFO

The in-situ evaluation of filter drains on the A50 network was undertaken in early 2016 targeting a 2km stretch of HFDs located at Blythe Bridge bypass. This part of the A50 DBFO network was opened to traffic in 1975 and no major reconstruction or rehabilitation of HFDs appears in records held by the road operator. This suggests that after approximately 30 years of operation, aggregate backfill is expected to be reaching (or even has surpassed) its intended service life. To carry out the condition assessment trial, a window sampler was used to collect HFD backfill aggregate samples of 87mm diameter. Seven locations across the 2km section were identified (based on visual evaluation and historic maintenance records) and subsequently used to extract the material. The sample tubes were sealed, marked and then transported to Loughborough University to further study and sieve.

Visual cues from the evaluated HFD lengths were suggesting highly fouled drains; surface crusting was evident for a large length of the evaluated drains along with extensive vegetation growth. Coupled with the long service period of this set of drainage assets, the investigation lead to surface cleansing, removal of excess vegetation and topping up drains with Type B aggregate material.

Table 7 summarises the results of the window sampling trial. All samples are split in two parts (upper and lower) to identify the extent of fouling levels differentiating between uppermost and basal bodies of the drainage trench. WSx-A samples thus correspond to the surface of the trench (typically between 200 and 300mm deep) whereas WSx-B results focus on the levels of fouling from material removed deeper from the drain.

Figure 20 exhibits window samples WS1 and WS5. In both cases a relatively small layer of material falling loosely within the range of Type B aggregate can be found in the uppermost 200-300mm of the sample. WS5-A is visibly less fouled (i.e. anticipated faster removal of

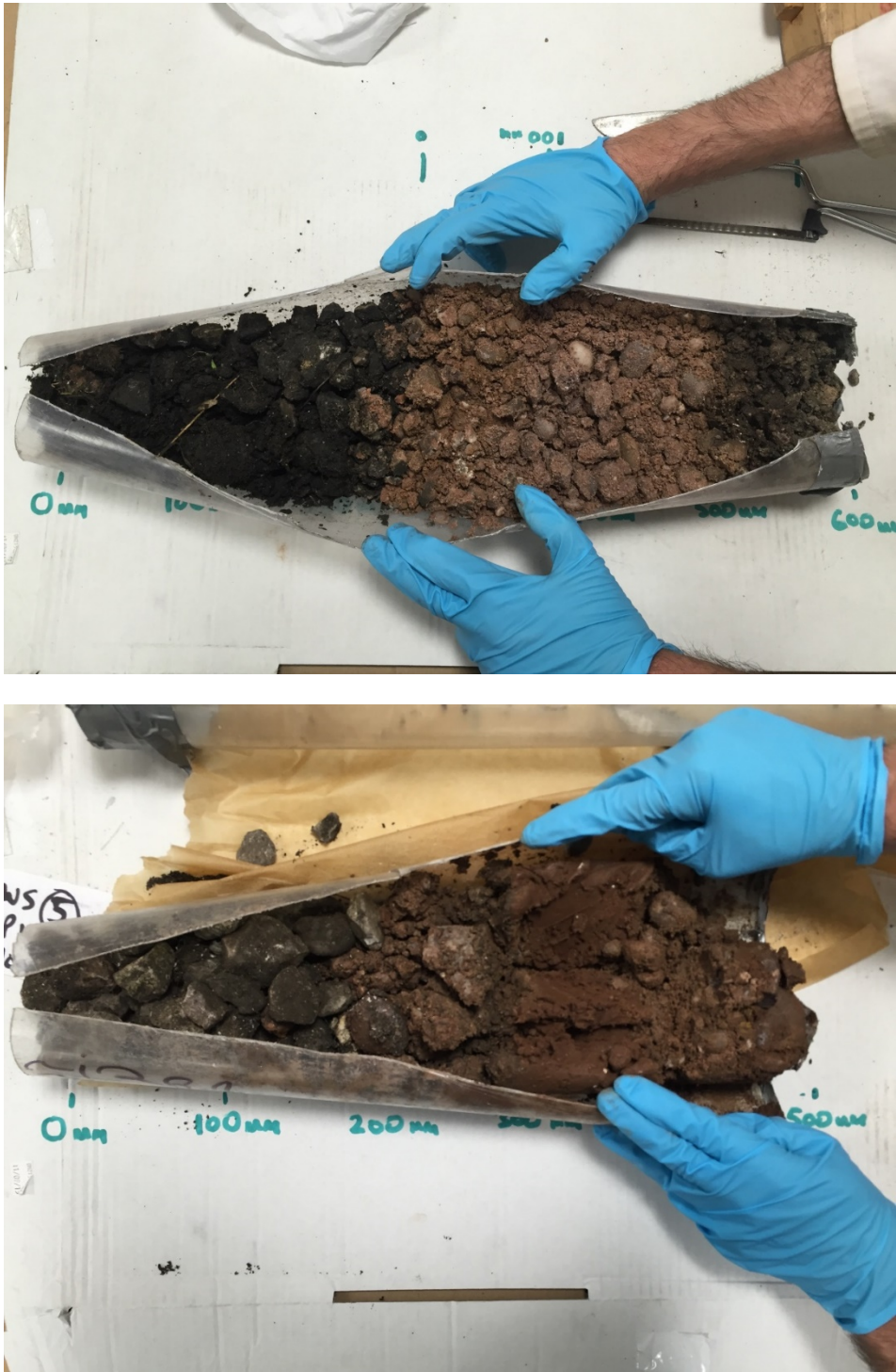


Figure 20 WS1 (top) and WS5 window samples

surface water) while the particle matrix of WS1-A is fouling dominated. For both WS1-B and WS5-B a thick layer of 300-400mm of predominately sand/clay based material is found directly below the uppermost backfill. This suggests the lower parts of both locations are

practically impermeable (relatively to anticipated drainage performance). The aggregate matrix composition of WS1 suggests that lengths of the trench could have been fouled during construction with the aggregate resembling sub-base rather than Type B backfill. All window samples collected exhibit high levels of sedimentation failing particle-grading requirements at every level.

Highway Filter Drains Maintenance Management

Table 7 Window Sampling A50 DBFO

Location	Material Passing Sieve Size (all mm)														
	63	40	31.5	20	16	14	10	6.3	4	2	1	0.5	0.25	0.125	0.063
Type A		100%		80-99%			50-90%		30-75%	15-60%		0-35%	0-4%		0-3%
Type B		80-99%		0-20%			0-5%								
WS1-A	100%	100%	100%	46%	30%	30%	24%	23%	20%	19%	17%	14%	9%	6%	4.6%
WS1-B	100%	100%	100%	89%	80%	80%	53%	46%	31%	26%	21%	17%	9%	5%	3.7%
WS2-A	100%	90%	80%	49%	40%	40%	32%	28%	23%	21%	17%	13%	8%	4%	2.6%
WS2-B	100%	100%	100%	96%	87%	87%	67%	56%	40%	33%	27%	21%	7%	3%	2.3%
WS3-A	100%	100%	100%	46%	30%	30%	24%	23%	20%	19%	17%	14%	9%	6%	4.6%
WS3-B	100%	100%	83%	33%	21%	21%	15%	14%	11%	10%	9%	8%	7%	6%	4.3%
WS4-A	100%	96%	83%	38%	32%	32%	30%	29%	26%	25%	24%	22%	16%	10%	6.9%
WS4-B	100%	100%	97%	57%	50%	50%	38%	34%	26%	22%	18%	15%	11%	8%	6.2%
WS5-A	100%	100%	100%	28%	20%	20%	14%	12%	10%	9%	7%	5%	3%	1%	0.5%
WS5-B	100%	85%	84%	72%	63%	63%	54%	49%	42%	39%	36%	33%	24%	17%	14.2%
WS6-A	100%	95%	81%	49%	44%	42%	35%	32%	28%	26%	24%	22%	18%	13%	10.4%
WS6-B	100%	98%	92%	57%	50%	49%	35%	30%	23%	21%	18%	15%	8%	5%	3.5%
WS7-A	100%	100%	100%	56%	38%	37%	25%	23%	22%	17%	15%	13%	10%	8%	5.5%
WS7-B	100%	100%	100%	94%	88%	85%	72%	66%	54%	49%	44%	40%	34%	31%	27.2%

4.3.4.2.4 Distress quantification

An essential component of asset condition assessment systems is the establishment and use of condition metrics that can quantify distress and link back to anticipated levels of asset performance. Such metrics are derived by studying the physical characteristics of deteriorated assets and can either be based on rating or measuring. Numerous examples of such metrics are available to the pavement or bridge engineer to monitor key assets and develop maintenance strategies following an engineered assessment of investment requirements and needs-based planning.

Deterioration mechanisms of HFD are generally understood in the wider highways sector. The intrusion of foreign material progressively limits the void space in a drainage trench and pavement runoff is re-diverted back to the pavement during rainfall events that surpass the drainage capacity of a failing HFD trench. Previous attempts to evaluate aggregate backfill focused on a qualitative assessment of particle size distribution curves that offers limited value in terms of drawing direct comparisons between large numbers of assessed samples. Figure 22 presents PSDs of all extracted window samples from the A50 site evaluation. It is clear that highly fouled samples are represented by lines that are further away from the Type B envelope.

For the purposes of developing an engineered deterioration metric, the extent of fouling retrieved from such samples is quantified with the aim to produce indices that reflect the level and influence of the introduced material. Such metrics should be easily attainable and different concepts have been proposed through this work (papers 1 to 4 in Appendices).

Of particular interest were metrics linked to the availability of free void space discussed in following sections and linked to ground penetrating radar. Without a universally acceptable methodology to assess existing assets, different techniques and approaches can be employed and in general terms these can be classified in either mass or volumetric based methods (see

Paper 4 Appendix D Section 2.2 **Railway Ballast Condition Evaluation**). The terminology as such is derived from railway ballast condition assessment techniques. There, mass based methods focus on establishing the extent of deterioration by quantifying the levels of fouling material on the premise of studying and assessing PSD curves; they are thus usually easy or straightforward to calculate. Volumetric based methods focus on identifying aggregate fill and fouling material properties and developing an index on the premise of void space and its progressive reduction in a given sample. In regards to drainage, a volumetric index can be easier to link to serviceability levels and anticipated performance with the availability of void space being a representative basis for drainage capacity. Such indices though require further testing and can be more complicated in some cases.

The key aim in using quantifiable metrics in evaluating HFD fouling, is the development of a method that will account for the level and influence of the fouling material, and can be easily calculated to characterise the condition of the drain linked to condition data collection techniques. In simple terms such a metric focuses on simplicity, accountability and repeatability. A condition index can simplify condition evaluation by eliminating subjectivity and enable the establishment of universal thresholds to be used for network wide studies and establishment of performance levels.

All concepts developed for filter drains are derived by studying fouled in-service samples and the collected fouling material which is separated from the HFD Type B backfill by means of sieving. The indices are then linked to anticipated drainage capacity (permeability) building upon the specified HFD aggregate grading requirements for fresh samples and typical PSD curves for fouled sections. This evaluation of performance is presented in the following section using reconstructed samples ranging in condition from excellent to very poor.

A few different options of mass based indices have been communicated throughout the work to CR and presented in papers 1 to 3 (appendices); mass based assessment approaches have been based on:

- Percentage Drain Fouling (PDF)
- Fouling Geometric Average (FGA)

PDF is calculated by identifying the fouling concentrations within the sample from an extracted PSD curve. The percentage of mass falling below the 10mm boundary is assumed to form the introduced foulant particle matrix. In the equation cited below, the 0.063mm size sieve is also used to introduce a higher weight to the fines concentration in the evaluated sample that would generally suggest a detrimental effect on drainage performance. The equation used to derive the index is as follows:

$$P_{DF} = P_{\%10mm} + P_{\%0.063mm}$$

Where:

- $P_{\%10mm}$ = Percentage by mass passing the 10mm sieve (as fouling material)
- $P_{\%0.063mm}$ = Percentage by mass passing the 0.063mm sieve.

The Fouling Geometric Average is extracted from PSD curves by calculating the weighted geometric mean of the particle size distribution of each evaluated sample; the derivation used in this case is defined as:

$$\bar{x} = \exp\left(\frac{\sum_{i=1}^n w_i \ln x_i}{\sum_{i=1}^n w_i}\right)$$

Where:

- \bar{x} = FGA
- w_i = Percentage of mass passing sieve aperture size
- x_i = Sieve aperture size

Location	PDF	FGA	RFV
WS1-A	28.60%	16.45	0.00
WS1-B	56.70%	14.81	0.00
WS2-A	34.60%	16.10	0.00
WS2-B	69.30%	14.08	0.00
WS3-A	28.60%	16.45	0.18
WS3-B	19.30%	20.00	0.54
WS4-A	36.90%	12.52	0.00
WS4-B	44.20%	14.74	0.00
WS5-A	14.50%	25.07	0.58
WS5-B	68.20%	9.48	0.00
WS6-A	45.40%	11.71	0.00
WS6-B	38.50%	15.91	0.00
WS7-A	30.50%	16.21	0.15
WS7-B	99.20%	8.11	0.00

Table 8 A50 Window samples classified using 3 proposed fouling indices.

A fresh sample exhibiting no signs of distress (hence limited fouling as defined by Type B aggregate envelopes) is expected to present a P_{DF} of no more than 10% and a FGA of no less than 27. Highly fouled section retrieved from the A30 site investigation from locations Eype and Charmouth present P_{DF} of 25.7%, 67% and FGAs of 18.78, 9.73 respectively. This suggests that for the two mass based indices, a higher P_{DF} or a lower FGA advocates increasing fouling concentrations. Table 8 summarises the results and presents window samples from A50 site investigation characterised by the indices proposed in the study.



Figure 21 Effect of increasing R_{FV} ; from left to right: $R_{FV} = 1$ $R_{FV} = 0.5$ and $R_{FV} = 0$

In line with ballast evaluation studies presented in the past (Brough et al., 2003, Feldman and Nissen, 2002, Sussman et al., 2012) a simplistic approach to estimate the available void space in a HFD sample was also proposed and discussed in Papers 1 to 4. The use of volumetric based fouling scales is first introduced in Appendix A – Section 2.2.1.2 Volume Based Indices, and then adopted in experimental work drawing parallels from Ballast condition evaluation literature. In Appendix B – Section 3.4 Evaluating Asset Distress And Introducing Condition Metrics For HFD, the concept is used to reinforce the case or measuring performance rather than simply rating for the purposes of detailed HFD investigation. Appendix C and Appendix D integrate the Free Voids Ratio (and other proposed fouling indices to a lesser extent) in GPR studies (also detailed in Section 4.3.4.4. in the main body of this thesis).

The derivation of Free Voids Ratio (R_{FV}), is based on material properties that can be extracted easily in a laboratory and used to evaluate condition information. The equation is described below:

$$R_{FV} = \frac{V_{VFRA} - V_F}{V_{VFRA}} = \frac{e_{fr}V_A - \frac{M_F}{\rho_f}}{e_{fr}V_A} = \frac{e_{fr} \frac{M_A}{G_A} - \frac{M_F}{\rho_f}}{e_{fr} \frac{M_A}{G_A}}$$

Where:

- V_{VFA} = an estimation of the volume of voids in fresh backfill,
- V_F = volume of the fouling material
- e_{fr} = void ratio for fresh Type B aggregate
- ρ_f = bulk (dry) density of foulant
- G_A = HFD backfill material specific gravity
- M_F = mass of fouling material
- M_A = mass of HFD backfill material

In simple terms, R_{FV} represents a normalised estimation of the available void space in a HFD sample. This will range from 0 to 1, 0 representing a material that is fully clogged (or spent) and hence presented with no available void space. A R_{FV} of 1 would suggest the opposite condition, that is a fresh sample. Gradually deteriorated backfill is presented in Figure 21; initially, $R_{FV} = 1$ represents fresh aggregate, $R_{FV} = 0.5$ a moderately fouled sample and $R_{FV} = 0$ Type B material that can be considered spent. The adoption of this metric is presented in Paper 3 (Appendix C) where a study linking drainage capacity and GPR response is defined. The results suggest that a correlation between the volumetric index, serviceability and non-destructive testing can be achieved in a practical way.

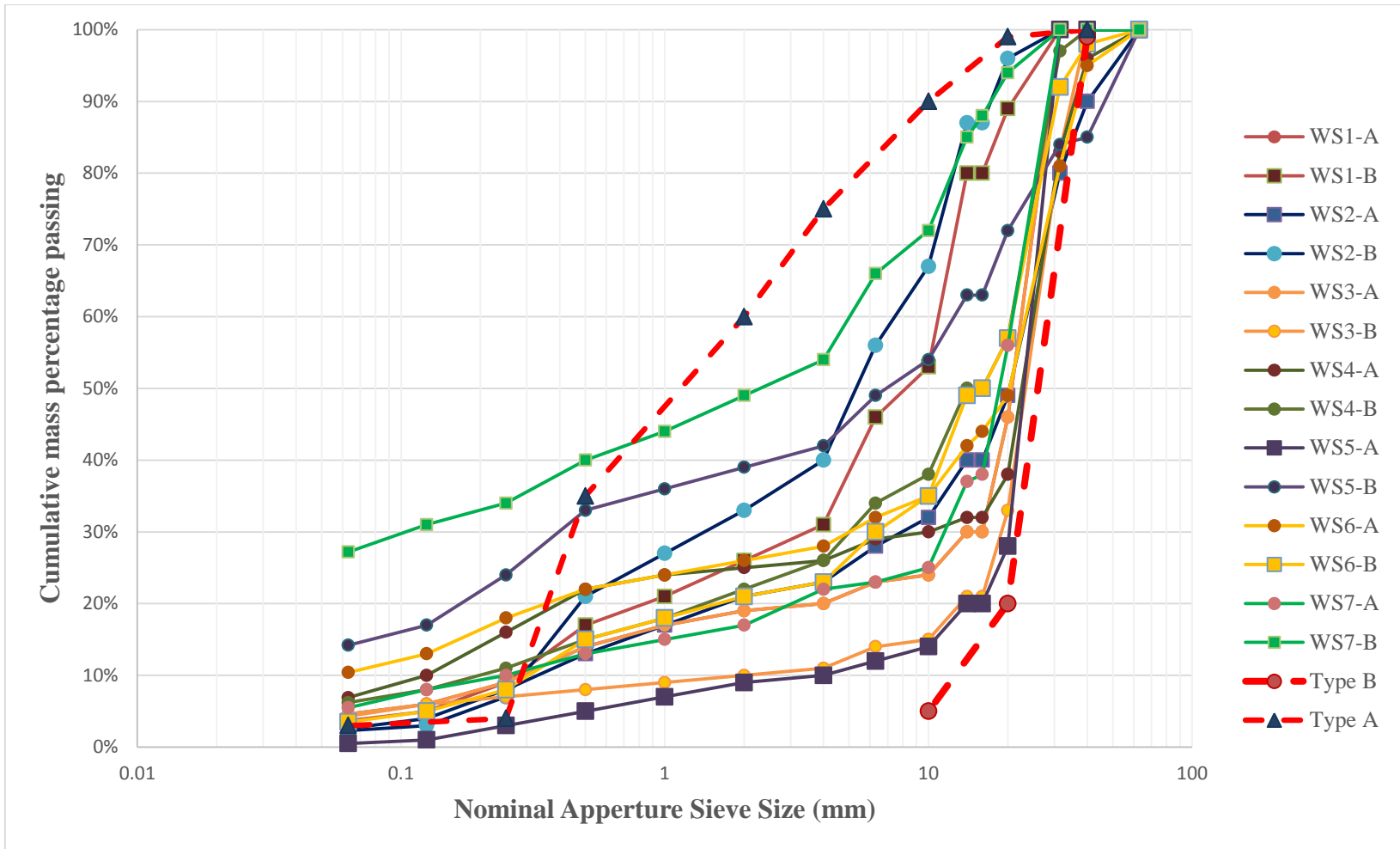


Figure 22 PSD curves of all A50 samples.

4.3.4.3 Hydraulic Trials

If fouling extent as a direct measurement of HFD deterioration can be linked to performance levels (drainage capacity), a condition evaluation framework accountable for the asset's degradation characteristics can be established. The methods of collecting the condition data should then be addressed in a way that reinforces asset management (AM) principles and allows the identification of drainage assets that offer low levels of service, the subsequent determination of the maintenance backlog and the definition of intervention planning and treatment options.

To define a correlation between proposed indices and anticipated drainage performance a series of large-scale hydraulic trials with a custom-designed permeameter were conducted in Loughborough University laboratories. The large-scale permeameter designed for this set of objectives (Figure 23, Figure 24) allowed for the measurement of hydraulic conductivity values of samples with a radius of 375mm and depth of 450mm with varying fouling levels under a relatively low constant head. The trials were carried out using low hydraulic gradients and samples are saturated 24 hours before extraction of data; this in line to relevant ballast fouling evaluation studies aiming to classify drainage capacity for coarse gravel by assuming laminar flows. The methodology is detailed in Papers 1 and 3.

A constant flow is achieved using a weir at the top of the tank and the permeability at each fouling state is extracted by measuring the trial time and flow for each test. Four manometers are installed on the permeameter to enable accurate measurement of head drops between the drainage layers of fill. In order to prevent fine particles from washing out of the tank, a geofabric was installed on top of uniformly graded coarse aggregate at the lower end of the permeameter (see schematic Figure 23). Vertical hydraulic conductivity values of different aggregate-foulant mixes are hence extracted and are used to simulate and define discrete

condition states representative of fouling levels mapped to an anticipated level of drainage performance. Figure 23 diagrammatically represents the engineered fouling used in the trials to simulate on site conditions along with fouling material collected from site evaluation studies on the M77/GSO DBFO.

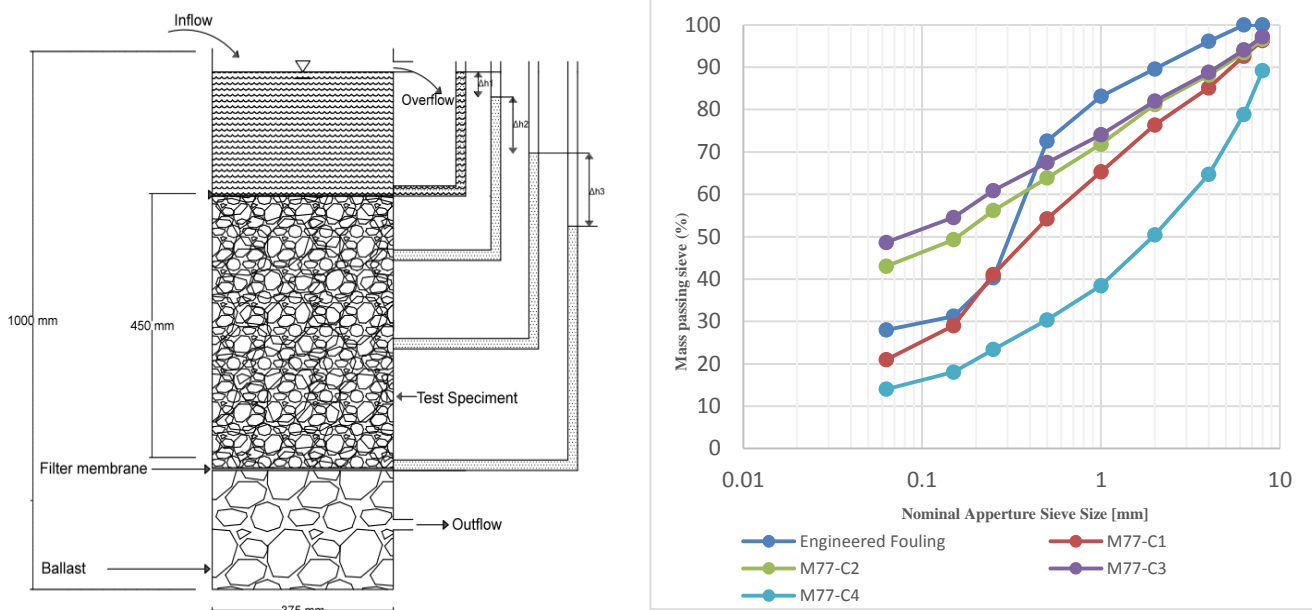


Figure 23 Schematic of large scale permeameter and fouling PSD curves collected from M77/GSO site and engineered at Loughborough University for permeability trials



Figure 24 Material Mixing at the lab and Permeameter used in trials

Figure 25 shows hydraulic conductivity of progressively fouled samples extracted from the laboratory trials; as expected the overall hydraulic conductivity of each sample reduces with increasing fouling levels (here presented as a function of Free Voids Ratio). To simplify data presentation and performance evaluation, Figure 26 shows the same dataset adopting now a normalisation value $K_{vmax} = 50 \text{ mm/sec}$ and a normalized hydraulic conductivity index $k' = k_v/K_{vmax}$.

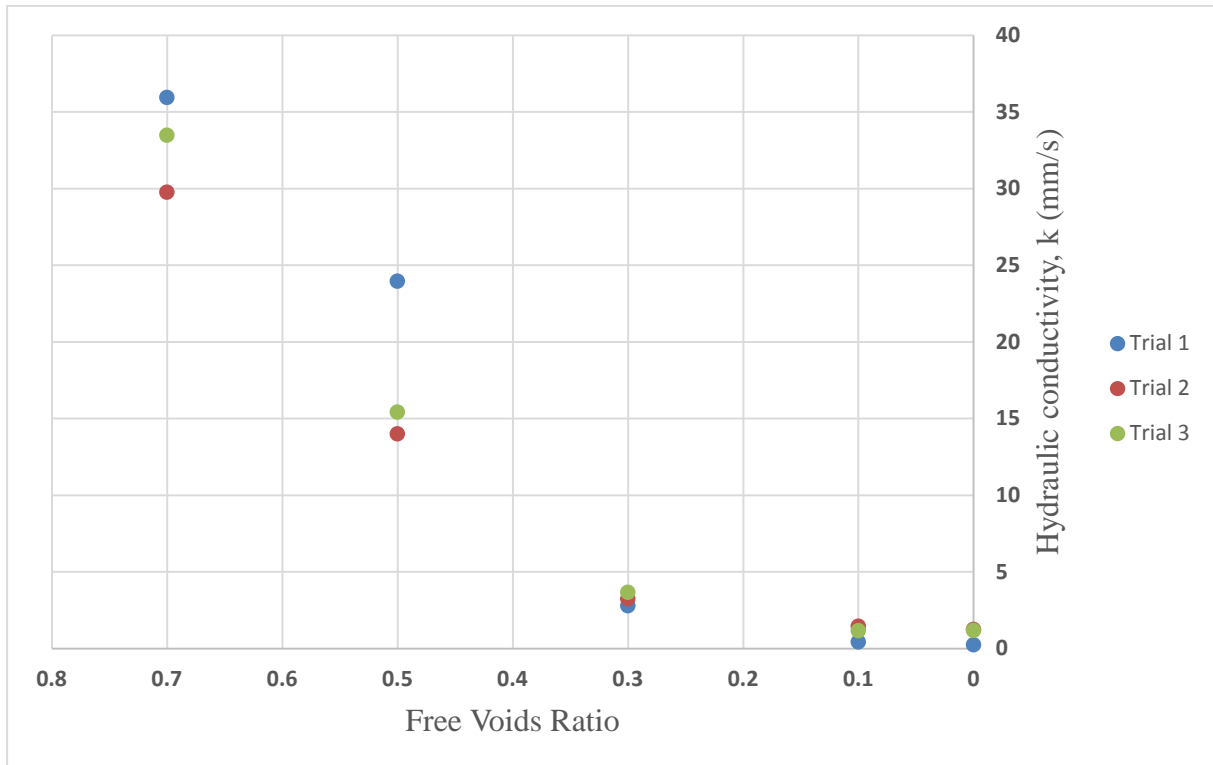


Figure 25 Variation of hydraulic conductivity values for decreasing Free Voids Ratio (K_{1-3} linked to trial with 3 measurements taken at each R_{fv})

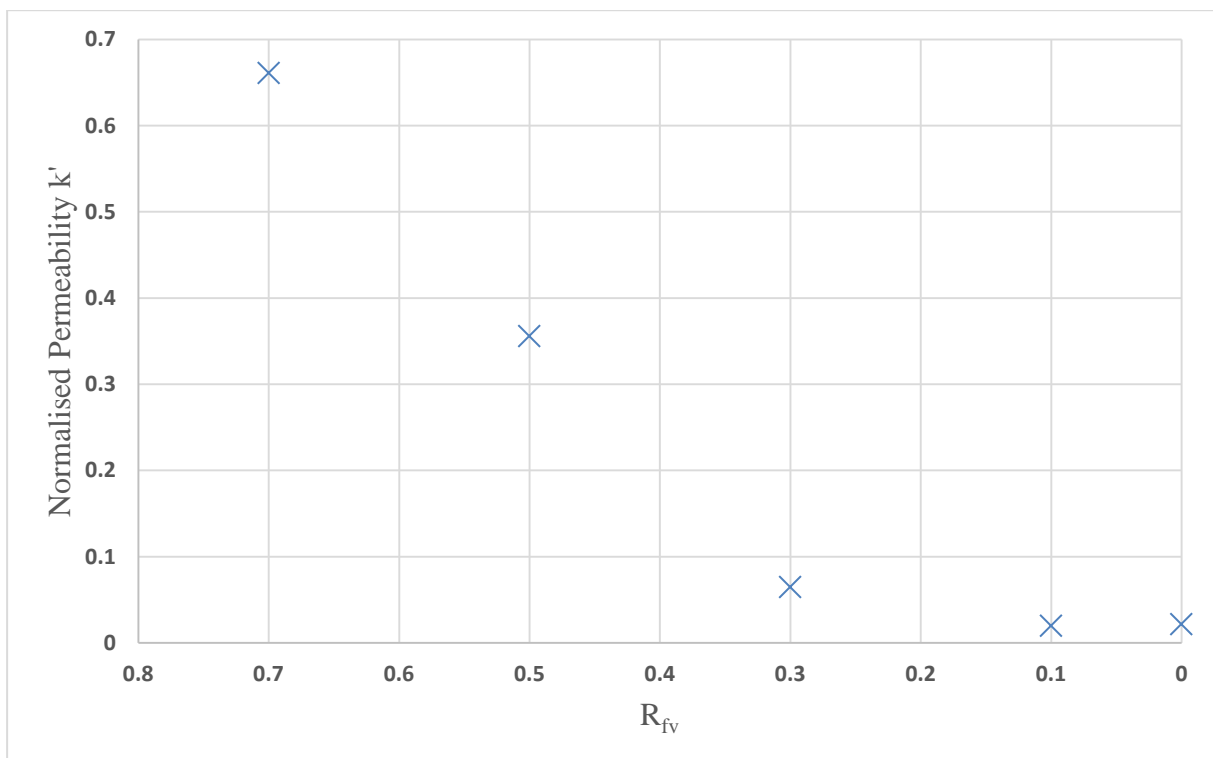


Figure 26 Normalised hydraulic conductivity values as a function of R_{fv}

From Figure 26 conclusions can be drawn for serviceability levels and drainage performance. R_{fv} values higher than 0.5 correspond to generally high permeability capacities (normalised k' values of circa. 0.4 assumed to suggest acceptable drainage capacity). These will be indicative of fresh or moderately fouled samples capable of presenting high levels of service. Beyond that point, k' readings drop significantly to reach levels representative of extensively fouled samples (considered problematic if found on site). For R_{fv} values below 0.3 it can be assumed that the material becomes foulant - dominated and presents extremely low (normalised) drainage capacity; in principle this will result in extremely low levels of performance and will be indicative of a HFD section that can be considered 'spent'.

While for in-service conditions there will be a number of parameters to take into account when drainage performance of a pavement section is considered, the vertical hydraulic capacity of the aggregate fill could potentially be used to predict the anticipated 'drainage efficiency' of a particular HFD trench. Table 9 below presents the condition band classification established for varying levels of R_{fv} linked to expected in-situ drainage performance. This is further discussed in Paper 3 which presents the alignment of condition classification using fouling scales, drainage capacity / performance using hydraulic trials and non-destructive testing and evaluation (Appendix C – see section 3.1 What to measure; fouling scales and drainage capacity).

Condition Band Descriptor	Anticipated Drainage Capacity	Free Voids Ratio
Fresh Aggregate	Free Draining	> 0.7
Moderately Fouled	No noticeable drop	0.4 – 0.7
Highly Fouled	Severely reduced	0.2 – 0.4
Spent Aggregate	Practically impermeable	< 0.2

Table 9 Condition Bands and anticipated drainage performance as a function of R_{fv}

4.3.4.4 Non Destructive Testing

A preliminary study of ground penetrating radar as an HFD assessment option is described in Paper 3 (Appendix C discusses the application of GPR in artificially fouled aggregate samples). Electrical properties of HFD backfill that will constitute the fundamental steps in adopting the technology in network level surveys are discussed in the publication; the basis of the work is founded upon the assessment of the changing EM response of increasingly fouled samples that can be linked to condition bands as a function of fouling scales and serviceability performance. The application of the GPR technology thus aims to bring together the fouling evaluation study, along with the assessment of hydraulic performance and proposition of serviceability capacity.

The study of permittivity (or dielectric constant) is carried out in a controlled laboratory environment using Type B aggregate (as the drainage medium), sand, clay and engineered fouling materials. Moisture was also studied in the trials and preliminary results suggest that its footprint is a key factor to be considered in any evaluation exercise. For the purpose of the examination, different aggregate containers and antenna configurations were explored most yielding comparable results (confirming acceptable repeatability of the data extraction). Figure 27 presents two different aggregate tanks used along with a 1GHz Ekko Pulse ground-coupled GPR system.

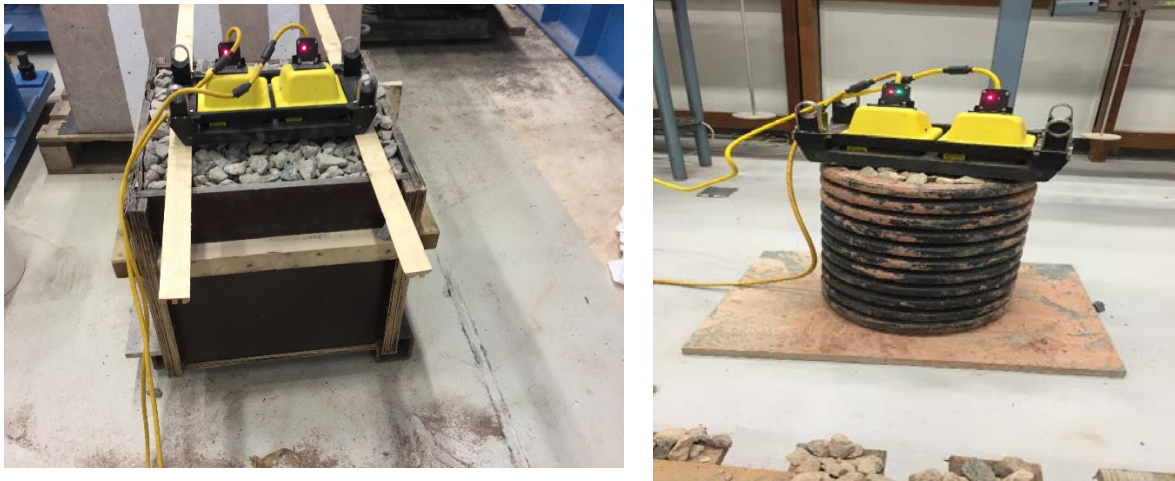


Figure 27 Aggregate containers used in dielectric evaluation study conducted with Type B aggregate material

Introducing sand, clay or the engineered fouling material along with moisture within the trial tank, caused distinctive reflection and propagation variations that were easily identified in a typical GPR time-domain waveform. Material boundaries can easily be extracted from a typical scan, due to the anticipated large peaks at air - aggregate and aggregate - steel plate interfaces, using simple post-processing filtering (time-zero correction and bandpass butterworth within the time domain). This can be seen in Figure 28 that demonstrates how propagation velocity varies as a function of fouling types and levels. The strong reflection identified in the graph as the steel plate reflection correlated to a pre-defined layer depth; the y-axis of the two figures represents time.

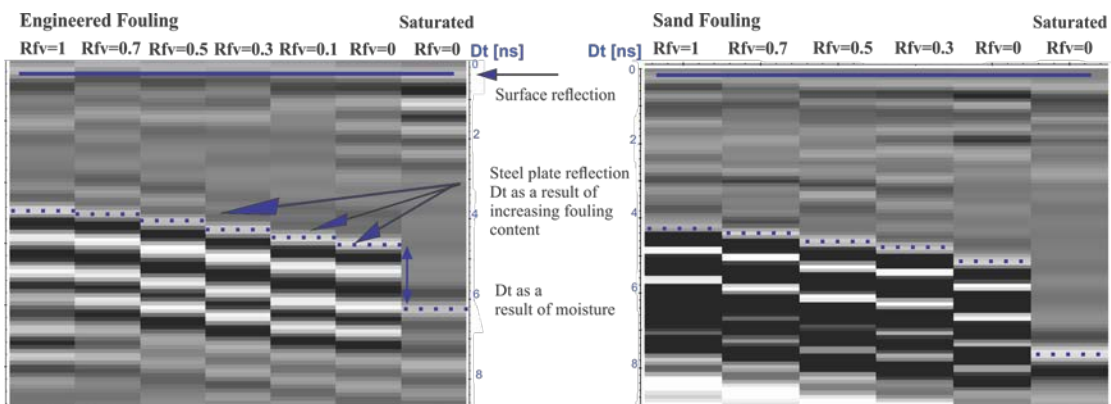


Figure 28 Radargrams of increasingly fouling material (using engineered fouling – left and sand fouling – right). Increased fouling forces EM to travel at lower speed through sample

The range of dielectric constant (ϵ_r) values as the aggregate condition moves from ‘fresh’ to ‘spent’ varies according to fouling type used. The permittivity values are calculated by measuring the two way travel time (by identifying reflections from air-aggregate and aggregate basal-steel plate interfaces) within the evaluated medium (known depth - 360mm) and then by calculating the wave speed u through the medium. The dielectric constant was then extracted adopting $u = c/\sqrt{\epsilon}$. From the preliminary set of GPR trials, ϵ_r for fresh aggregate was calculated to be equal to 3.06; using the engineered fouling the range between fresh and spent material, $\epsilon_{r,spent} - \epsilon_{r,fresh} = 1.6$. For sand fouling, the range of dielectric constants between the two condition extremes was calculated to be smaller, $\epsilon_{r,spent} - \epsilon_{r,fresh} = 1.2$. The use of clay fouling resulted in higher permittivity values and in general terms, a reduced R_{FV} (hence increased fouling) results in lower wave propagation velocities in the evaluated medium. A correlation between fouling levels (and to some extent types) and dielectric constant values can hence be achieved for condition data extraction purposes.

A clearer deviation of the electrical property of the aggregate-fouling mix was apparent in the study when water was introduced in the evaluation tanks. The dielectric constant was visibly more sensitive to water rather than increasing fouling levels. These observations are visualised qualitatively in the profiles presented in Figure 28. A discussion about the effect of moisture in the permittivity study can be found in Paper 3 (Appendix C). Here the importance of moisture content for site evaluation studies to eliminate sources of error in a condition survey is highlighted; high dielectric constant values are indicative of fouling but could also be linked to moisture content.

Condition Descriptor	ϵ_r	
	Engineered Fouling	Sand Fouling
Fresh Aggregate Dry	3	
Fresh Aggregate Wet	4	
Spent Dry	>4.6	>4.2
Spent Wet	8.8	8.5

Table 10 Dielectric constant values for Type B aggregate as a function of condition and water content

In follow-up trials, condition assessment of Type B aggregate backfill focused on the scattering evaluation of the aggregate fill. Following the principles established from ballast studies (described in literature review and further discussed in Paper 4 – Appendix D see section 2.2.3 Engineering Applications: Railways) laboratory experimentation was designed to study the correlation of fouling levels and decreasing scattering from available void space in the fill. Scattering events result from the when the incident wave travels through a medium with large voids, much like a HFD trench backfill. This phenomenon has been studied extensively in ballast assessment studies and has been adopted to enable condition data extraction.

To investigate this application on HFD backfill, a large tank was built to carry out a set of laboratory trials. The tank’s internal dimensions were for this trial 1.2m deep x 2m long x 0.7m wide. Literature pertaining to the fundamental principles supporting the adoption of the particular experimental methodology (and subsequently adoption of this condition assessment methodology) along with results can be found in Appendix D and Appendix E (both papers 3 and 4 describe GPR applications in condition evaluation studies).

A representation of the scattering from voids in the designed medium for an incident wave that travels through a fresh aggregate to a section that is spent can be seen in Figure 29. This represents an A-scan extracted from the designed tank. The intensity of the amplitude

envelope applied on the extracted A-scans (a plot of a GPR trace as a function of time) is smaller once the wave enters the highly fouled section. The large peak at the bottom end of the plot is a result of the steel plate producing high reflections. The amplitude reduction from extracted traces can hence be correlated to increasing fouling levels assuming that the total energy attenuation can be attributed to deteriorating sections.

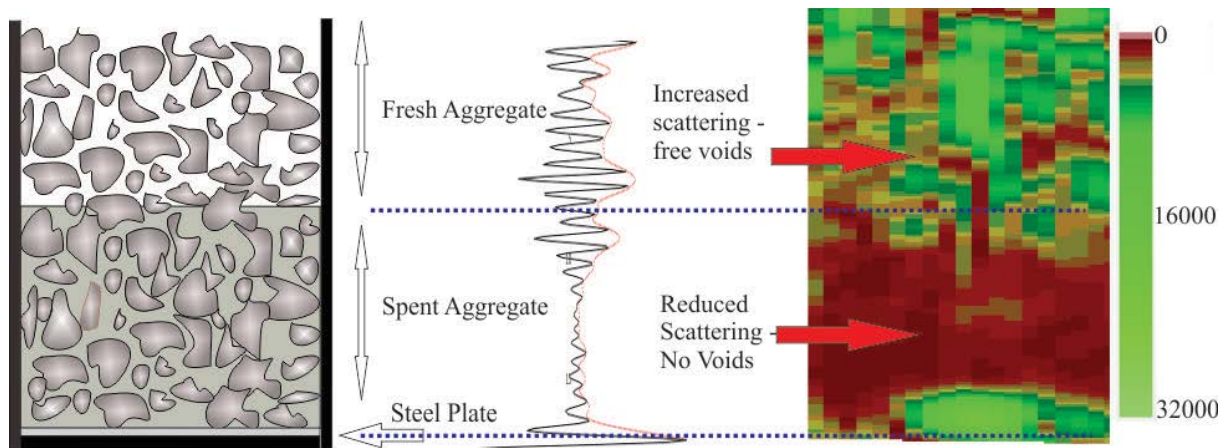


Figure 29 Scattering from voids and attenuation as wave travels from 'fresh' to 'spent' aggregate.

Representation of typical A scan and ReflexW scattering amplitude graph

Different fouling and water content cases were evaluated in the study; these are diagrammatically presented in Figure 30. Fresh or relatively clean sections produced significant scattering; large amplitude peaks are apparent for EM traces traveling through sections with $R_{fv} > 0.5$. This can be observed in all uppermost layers in Case A throughout all three sections of the pseudo-trench. The increasing fouling levels in sections B,C in Case B (R_{fv} moves from 1 to 0.5 for uppermost layers of Section B and from 1 to 0.6 for uppermost layers of Section C) have an impact on the EM wave and increased attenuation is observed albeit scattering events are still noticeable. By further increasing fouling levels in section B for the last dry set of evaluated fouling conditions (R_{fv} for uppermost layer now 0) a further reduction in scattering intensity is noticeable. Throughout the three cases (A to C) the fouling levels of section A remains unchanged providing a baseline reading for the trial.

When water was introduced in the box (allowed to percolate through the fill from the top) in Case D, the wave's velocity is expected to decrease (so two way travel times increase) and the amplitude peaks in the saturated aggregate/fouling parts diminish. Looking at Figure 30, the lowest radagram set (Case D) presents the case of two wet sections that in previous cases would be presented with a significant scattering indicative of available void space. In the wet sections trial, scattering is weakened (almost impossible to notice) and the basal steel plate reflections are hardly identified.

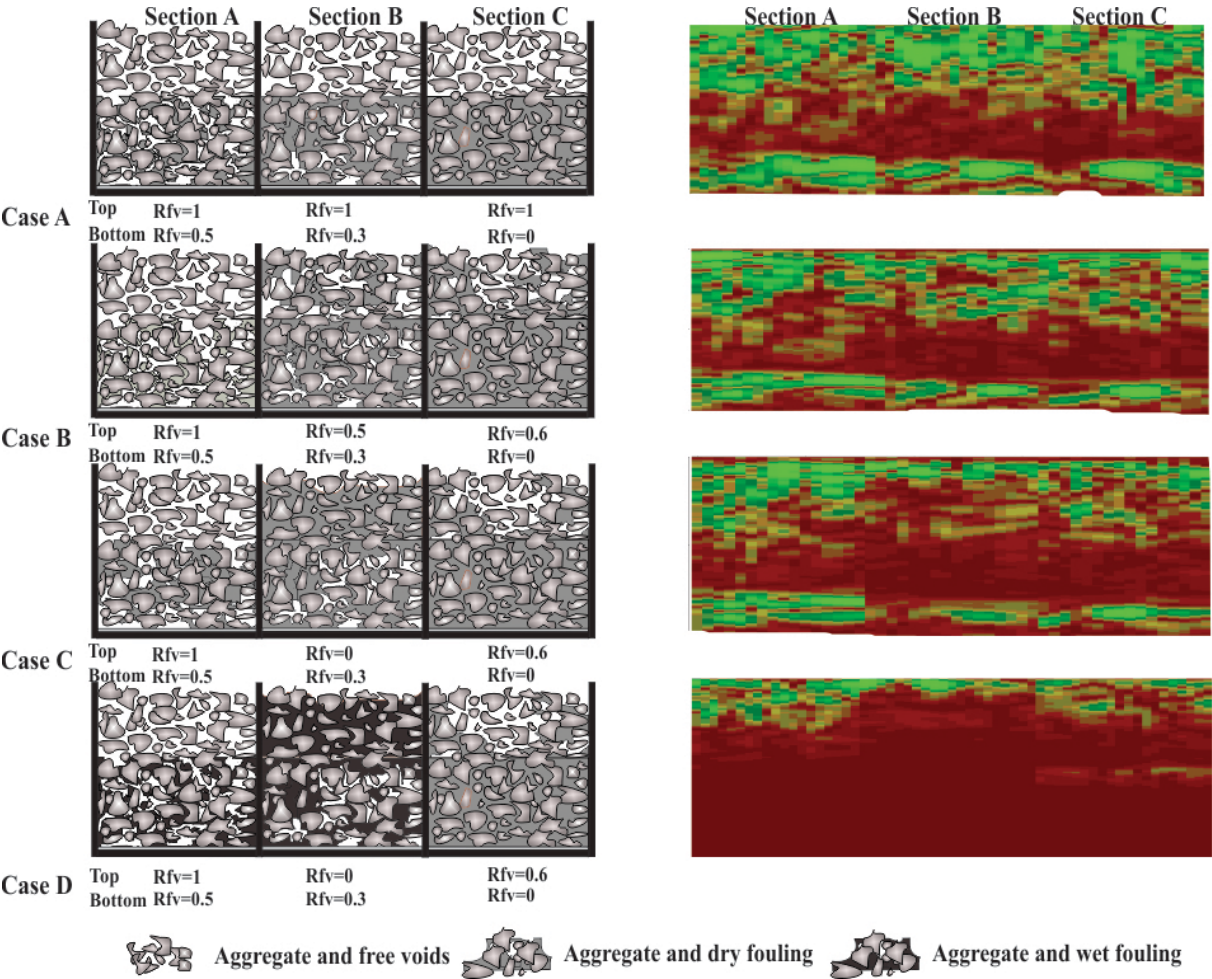


Figure 30 Scattering Evaluation output; 4 cases presented each varying in degree and extent of sedimentation and water content

4.3.5 CONDITION PROGNOSIS

In respect to the strategic framework defined in Section 4.3.2, Condition Prognosis relates to the modelling techniques, condition information and failure modes and loss of function system packages. Within any proactive maintenance planning system, condition, performance and anticipated loss of function are interconnected and mapped into a forward planning module that enables network wide (and often project-level specific) condition distribution projection.

By identifying failure modes (Section 4.3.4 and discussed in Paper 1 and Paper 2) and building the relevant condition states to be used, a probabilistic Markovian approach for deterioration projection was proposed to depict condition prognosis for HFD across the A50 DBFO. This is based on assumptions similar to what has been used for the formulation of the internal DST toolkit for the M77/GSO DBFO pavement network (also presented in Section 4.2). The decision to adopt Markovian probabilistic modelling to quantify HFD ageing was supported by the extensive adoption of this particular methodology in numerous examples of academic studies and/or state of practise deterioration projection outputs linked to either pavement or ancillary assets. The technique enables an easy transition to deterioration modelling and allows for flexibility and visibility, factors considered central to decision making at an early stage of this work.

Figure 31 conceptualises six discreet HFD condition bands along with the currently used maintenance options that restore the condition of the drains from a downstream band (lower drainage capacity), to an upstream condition (higher drainage capacity). The four main states proposed here are excellent condition, fair condition, poor condition and very poor condition with two subcategories representing the top-down failure modes: fair crusted and poor crusted (EC, FC, PC, VPC, FCC and PCC, respectively). The two crusted condition bands are critical

for safety reasons and are introduced here to enable separation of the two identified failure modes through network surveys and previous field studies. Lastly, the very poor condition represents an HFD section that has surpassed its projected service life (reduced surface and subsurface drainage capacities) and which presents a foulant - dominated aggregate fill. A representation of these states can also be seen in Table 3.

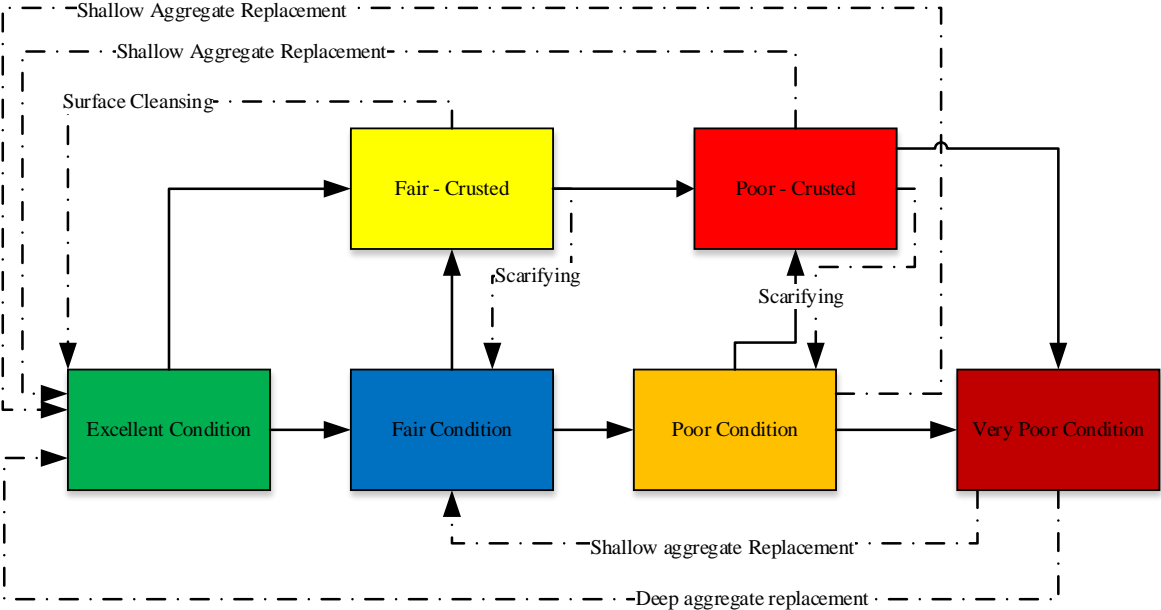


Figure 31 Ageing – Renewal Model developed for deterioration forecasting merging six discrete HFD condition bands and Maintenance options currently used in the wider sector

The development of the TPM for HFD deterioration requires two variables: a pre-defined service life (L) and the number of condition bands (n) to be used in the analysis. Design manuals suggest the operational life of HFD sections to be approximately 10 years. Long stretches of HFD sections across CR’s networks surpassing this projection henceforth different service lives are evaluated in the analysis. Calibrating and fine-tuning a network-specific TPM requires the continuous collection of condition data and recording of actual failures and past maintenance. The probability matrix was calculated using the following equation.

Using this TPM and adopting a base condition vector to denote a HFD condition breakdown $a_0 = [EC, FC, FCC, PC, PCC, VP] = [1, 0, 0, 0, 0, 0]$, HFD ageing as a function of service life can be projected as shown in Figure 32.

$$P = \begin{bmatrix} p_{11} & p_{12} & \cdots & p_{1n} \\ p_{21} & p_{22} & \cdots & p_{2n} \\ \vdots & \dots & \ddots & \vdots \\ p_{n1} & p_{n2} & \cdots & p_{nn} \end{bmatrix}$$

$$= \begin{bmatrix} & \mathbf{EC} & \mathbf{FC} & \mathbf{FCC} & \mathbf{PC} & \mathbf{PCC} & \mathbf{VP} \\ \mathbf{EC} & 1 - \left[\frac{n-1}{L}\right] & \left(\frac{n-1}{L}\right)/2 & \frac{n-1}{L}/2 & 0 & 0 & 0 \\ \mathbf{FC} & 0 & 1 - \left[\frac{n-1}{L}\right] & \frac{n-1}{L}/2 & \frac{n-1}{L}/2 & 0 & 0 \\ \mathbf{FCC} & 0 & 0 & 1 - \left[\frac{n-1}{L}\right]/2 & 0 & \frac{n-1}{L}/2 & 0 \\ \mathbf{PC} & 0 & 0 & 0 & 1 - \left[\frac{n-1}{L}\right] & \frac{n-1}{L}/2 & \frac{n-1}{L}/2 \\ \mathbf{PCC} & 0 & 0 & 0 & 0 & 1 - \left[\frac{n-1}{L}\right] & \frac{n-1}{L} \\ \mathbf{VP} & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

Evidently smaller service lives would indicate faster deterioration rates, with parts of the network reaching unacceptable condition states earlier in the projected planning horizon. Using network experience and collating past maintenance records and existing condition distributions across the A50 DBFO, service lives of 10 and 25 years were rejected as too short and too long respectively. They are presented here though as a means of evaluating different risk profiles aligned to varying deterioration projections (and projected service lives accordingly). A conservative approach would suggest the adoption of $L = 15$. For the purpose of this work, $L = 15$ and $L = 20$ were used to extract follow up maintenance needs and establish network level M&R strategies (using best and worst case scenarios).

The use of the two extreme scenarios (in this case $L = 25$ and $= 10$) enables the comparison between all four deterioration rate scenarios as these are integrated in the DST tool developed. Figure 32 depicts deterioration patterns at the network level adopting the four proposed

service lives; a service life of 10 years used with the proposed TPM, would suggest over 80% of the HFD length across the network would require full reconstruction. In contrast, a service life of 25 years leads to minimal (and perhaps unrealistic) renewal requirements with over 50% of the HFD network still being characterised in the upper condition band levels (Excellent, Fair and Fair Crusted condition).

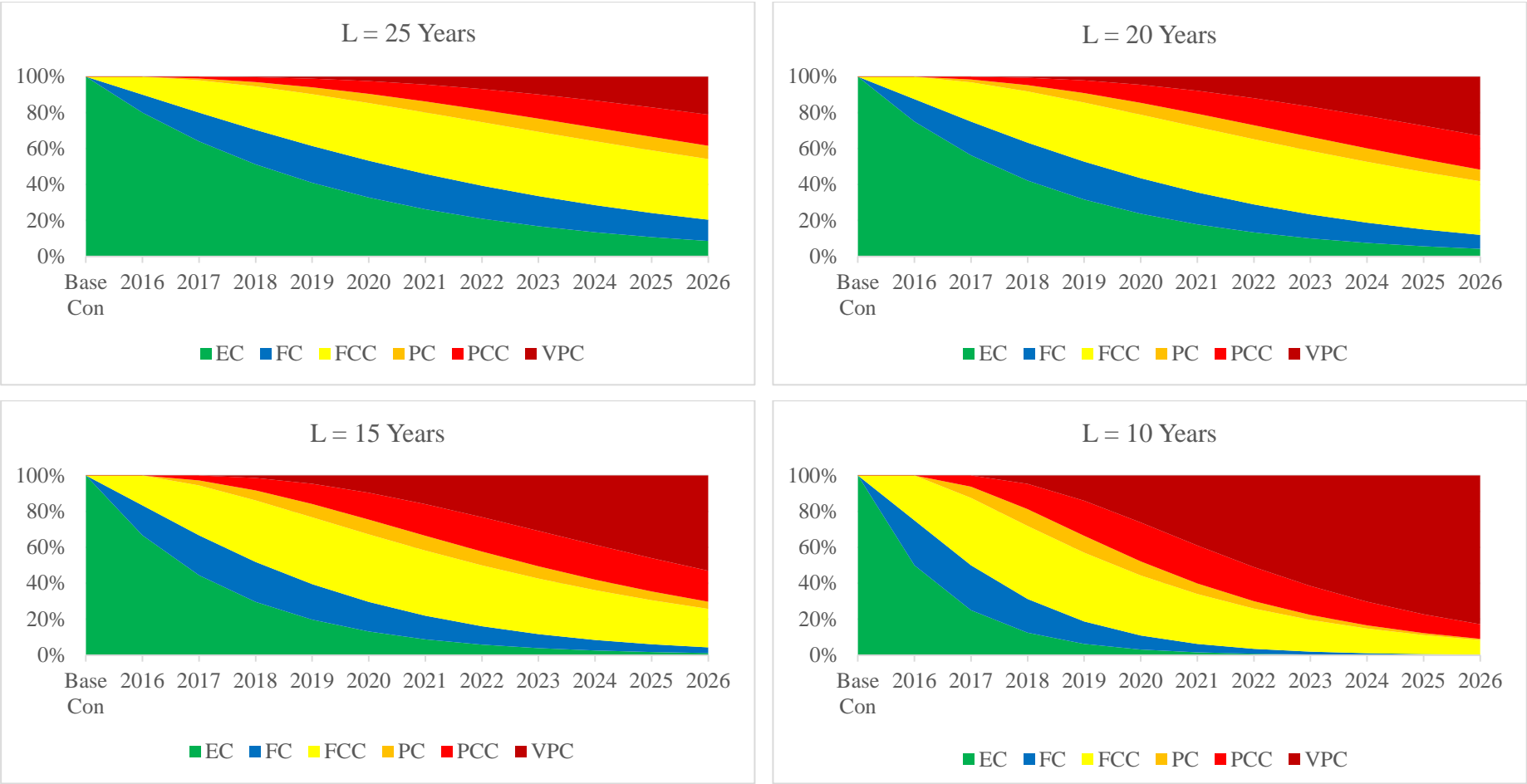


Figure 32 Network Level deterioration projection adopting four different service lives and HFD TPM using six condition bands

4.3.6 HFD MAINTENANCE DECISION SUPPORT TOOL

Central to AM systems are asset renewal and replacement analysis methods. These are tools that enable efficiency assessments and impact evaluation of all (M,R&R) actions. Such assessments will exhibit the effect of a particular M,R&R strategy on the current and future condition (the positive effect of maintenance) mapped against anticipated project costs. For the purpose of the study, a CR-internal DST was developed to integrate all aspects of the proactive MM system and to enable maintenance planning and investment allocation and prioritisation at the network level. The generic structure of the DST can be seen in Figure 33. Initially and for the purpose of the study, the system was considered for integration within CR's proprietary pavement management DST. While the option still remains plausible as a 'going-forward' AM task, for the needs of this work a more 'visual' and user-friendly interface was adopted. Hence an excel – based toolkit was developed meriting an easily objective - adaptable structure and clear and visual break-down of inputs, processing routines and outputs.

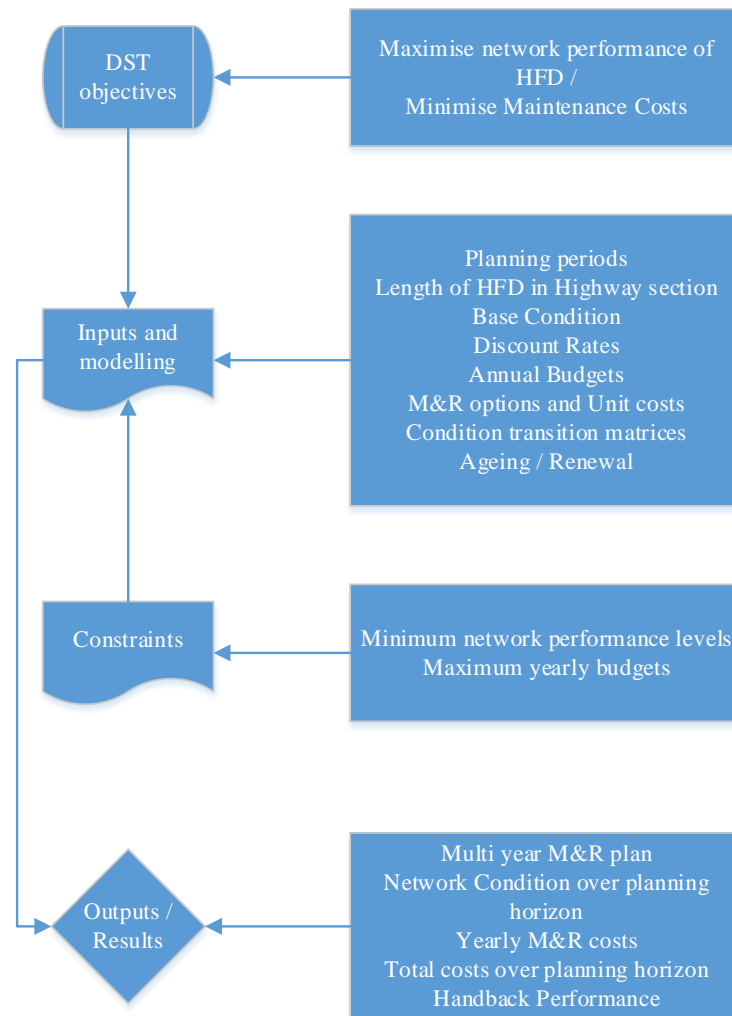


Figure 33 Structuring of DST to be used for HFD M&R planning

Different types and sources of information have been used to develop the decision support tool and these link to performance requirements, maintenance options and available annual budgets. In its final form the DST takes shape by integrating the available information into the excel spreadsheet that is linked to an add-in that enables the use of Genetic Algorithms (Palisade Corp, 2016) to solve the optimisation. The general layout of the DST developed can be seen in Figure 34.

To evaluate maintenance requirements based on the proposed probabilistic deterioration projection, the four service lives presented in the previous section (Figure 32) are adopted in the optimisation process. Scarifying, cleansing, shallow and deep replacement are used as maintenance options; unit rates for all options are derived from annual management accounts

and past maintenance records. The base condition vector used in this comparative study will be: $a_0 = [EC, FC, FCC, PC, PCC, VP] = [0.4, 0.4, 0.1, 0.1, 0, 0]$. Under this scenario, TPMs for the four service life variations are calculated to be:

- $L=25 \Leftrightarrow P = \begin{bmatrix} 0.8 & 0.1 & 0.1 & 0 & 0 & 0 \\ 0 & 0.8 & 0.1 & 0.1 & 0 & 0 \\ 0 & 0 & 0.9 & 0 & 0.1 & 0 \\ 0 & 0 & 0 & 0.8 & 0.1 & 0.1 \\ 0 & 0 & 0 & 0 & 0.8 & 0.2 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$

- $L=20 \Leftrightarrow P = \begin{bmatrix} 0.75 & 0.125 & 0.125 & 0 & 0 & 0 \\ 0 & 0.75 & 0.125 & 0.125 & 0 & 0 \\ 0 & 0 & 0.875 & 0 & 0.125 & 0 \\ 0 & 0 & 0 & 0.75 & 0.125 & 0.125 \\ 0 & 0 & 0 & 0 & 0.75 & 0.25 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$

- $L=15 \Leftrightarrow P = \begin{bmatrix} 0.667 & 0.167 & 0.167 & 0 & 0 & 0 \\ 0 & 0.667 & 0.167 & 0.167 & 0 & 0 \\ 0 & 0 & 0.833 & 0 & 0.167 & 0 \\ 0 & 0 & 0 & 0.667 & 0.167 & 0.167 \\ 0 & 0 & 0 & 0 & 0.667 & 0.333 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$

- $L=10 \Leftrightarrow P = \begin{bmatrix} 0.5 & 0.25 & 0.25 & 0 & 0 & 0 \\ 0 & 0.5 & 0.25 & 0.25 & 0 & 0 \\ 0 & 0 & 0.75 & 0 & 0.25 & 0 \\ 0 & 0 & 0 & 0.5 & 0.25 & 0.25 \\ 0 & 0 & 0 & 0 & 0.5 & 0.5 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$

The Research Undertaken

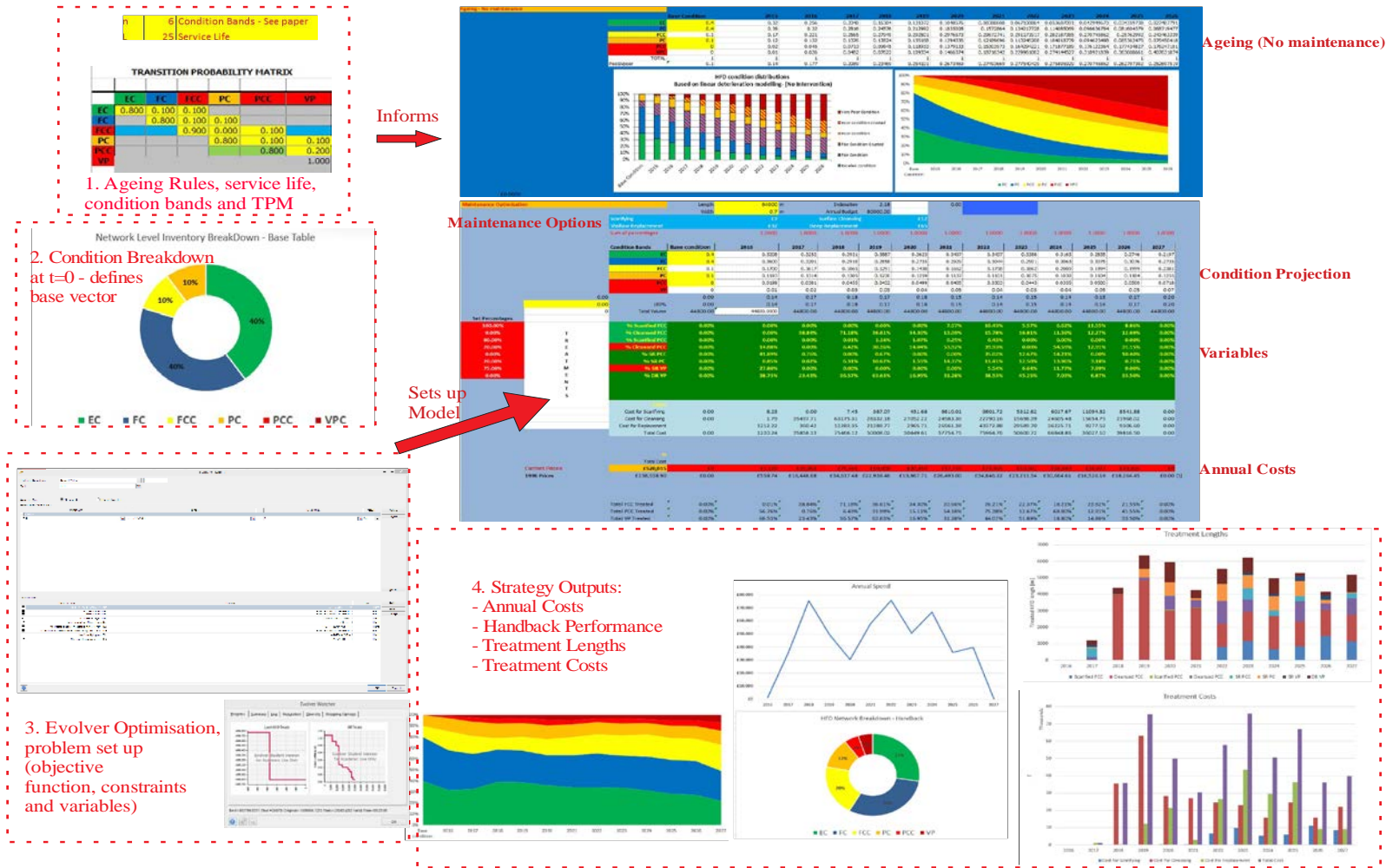


Figure 34 DST elements developed for HFD maintenance planning

Constraints in the optimisation routine were introduced to limit Very Poor, Poor Crusted, Poor and Fair Crusted condition across the HFD network. The ‘allowed’ performance threshold differs as a function of the constrained condition band; 20% of the HFD length can for example be allowed at a fair crusted condition where 5% of the total length can deteriorate to a Very Poor Condition. A comparison of annual maintenance requirements and performance projections as extracted post-optimising can be evaluated in Table 11. Total maintenance costs over a ten-year period for each evaluated service life are calculated to be:

- L=25: Total Maintenance Spend = £520,015
- L=20: Total Maintenance Spend = £651,287
- L=15: Total Maintenance Spend = £1,138,119
- L=10: Total Maintenance Spend = £1,679,755

All presented figures and annual costs are based on 2017 (current) prices. The toolkit also enables the discounting of total maintenance costs adopting indexations rates extracted from BBI’s finance accounts.

The Handback Performance Column presented on the table, depicts the projected network condition breakdown of the HFD network across the road concession being evaluated. Lastly the performance projection tracks the annual change of performance under the selected strategy that has been cost-minimised and constrained to reflect anticipated network performance / serviceability.

Service

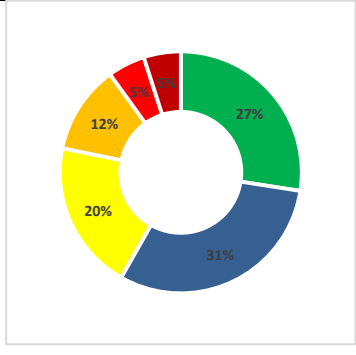
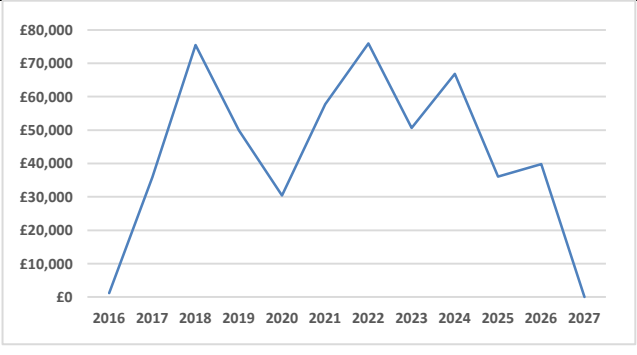
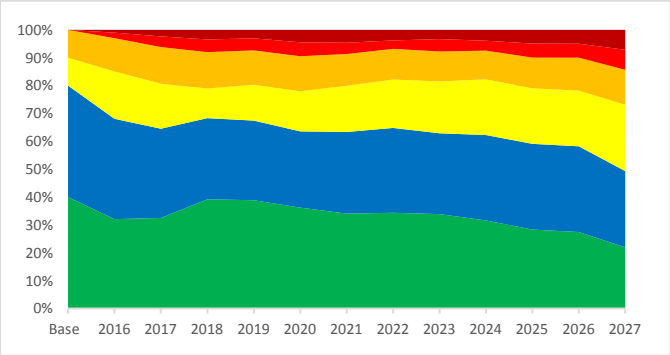
Performance Projection

Annual Costs

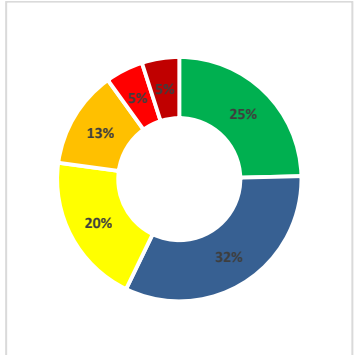
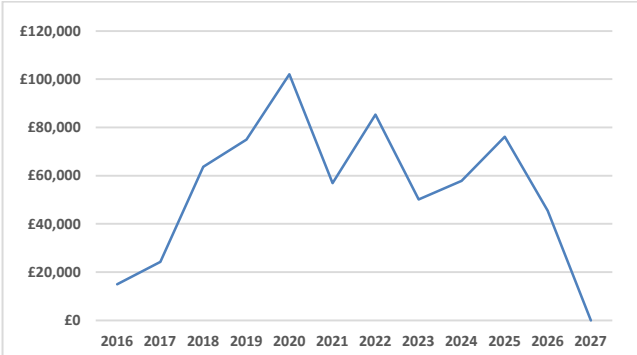
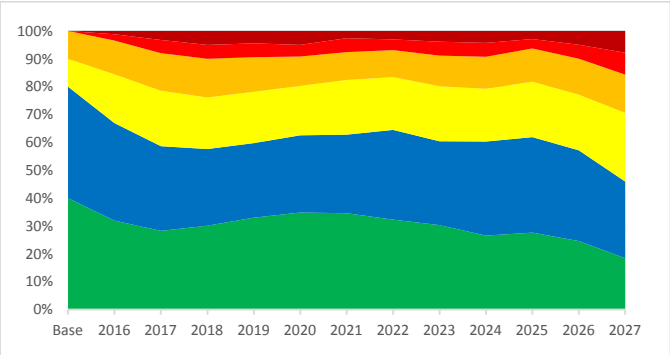
Handback Performance

Life

L=25



L=20



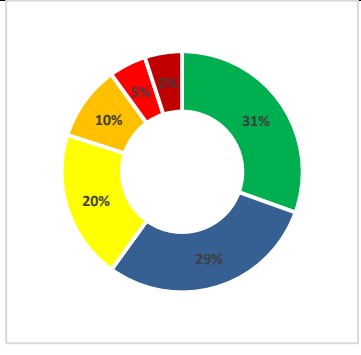
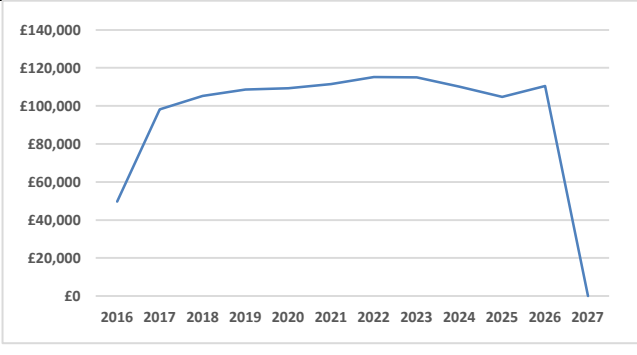
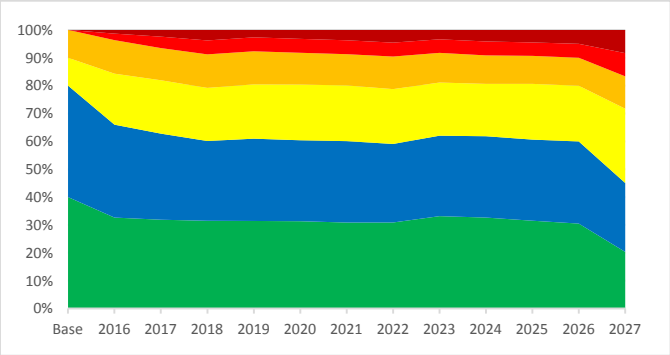
Service
Life

Performance Projection

Annual Costs

Handback Performance

L=15



L=10

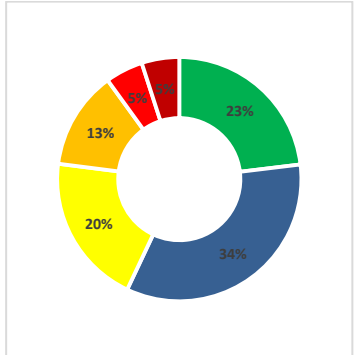
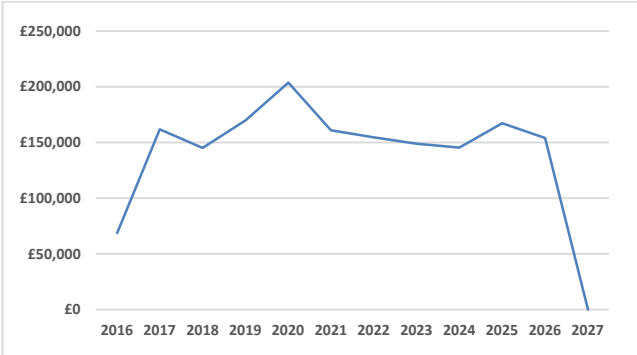
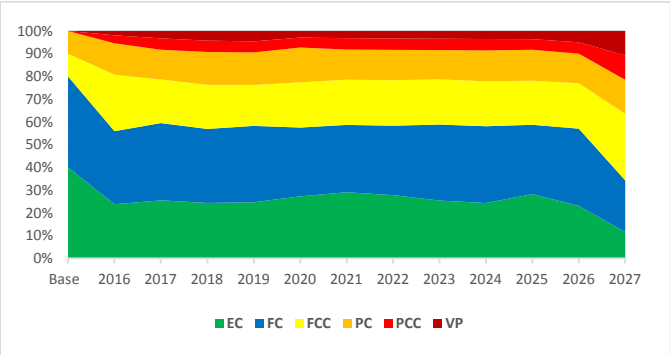


Table 11 DST output as a function of service life projection

Relaxing the constraints, or changing allowable percentage of HFD lengths in a given ‘failed’ condition band has a clear effect on the total maintenance investment requirements. For all four scenarios, handback performance (displayed on Table 11) and annual budgets are driven by constraints introduced in the model; the structure of the DST enables changing these constraints if required by modifying the parameters established within the Evolver add-in. In the presented analysis not more than 5% of the HFD network can reach a Very Poor Condition and similarly not more than 20% can reach a Fair Crusted Condition (given that the later poses lower risks of failure a higher percentage was deemed acceptable for in-service and handback criteria).

Focusing on the two service lives that (given CR’s network understanding and empirical knowledge) present more realistic in-service deterioration rates ($L=20$, $L=15$), the Treatment Length graphical output enables the establishment of maintenance needs and long-term material requirements. Table 12 presents examples of HFD lengths requiring rehabilitation or maintenance across a given network (in this case 60km of HFD lane-length); from the comparison it is visible that the reduced projected service life ‘forces’ higher maintenance lengths.

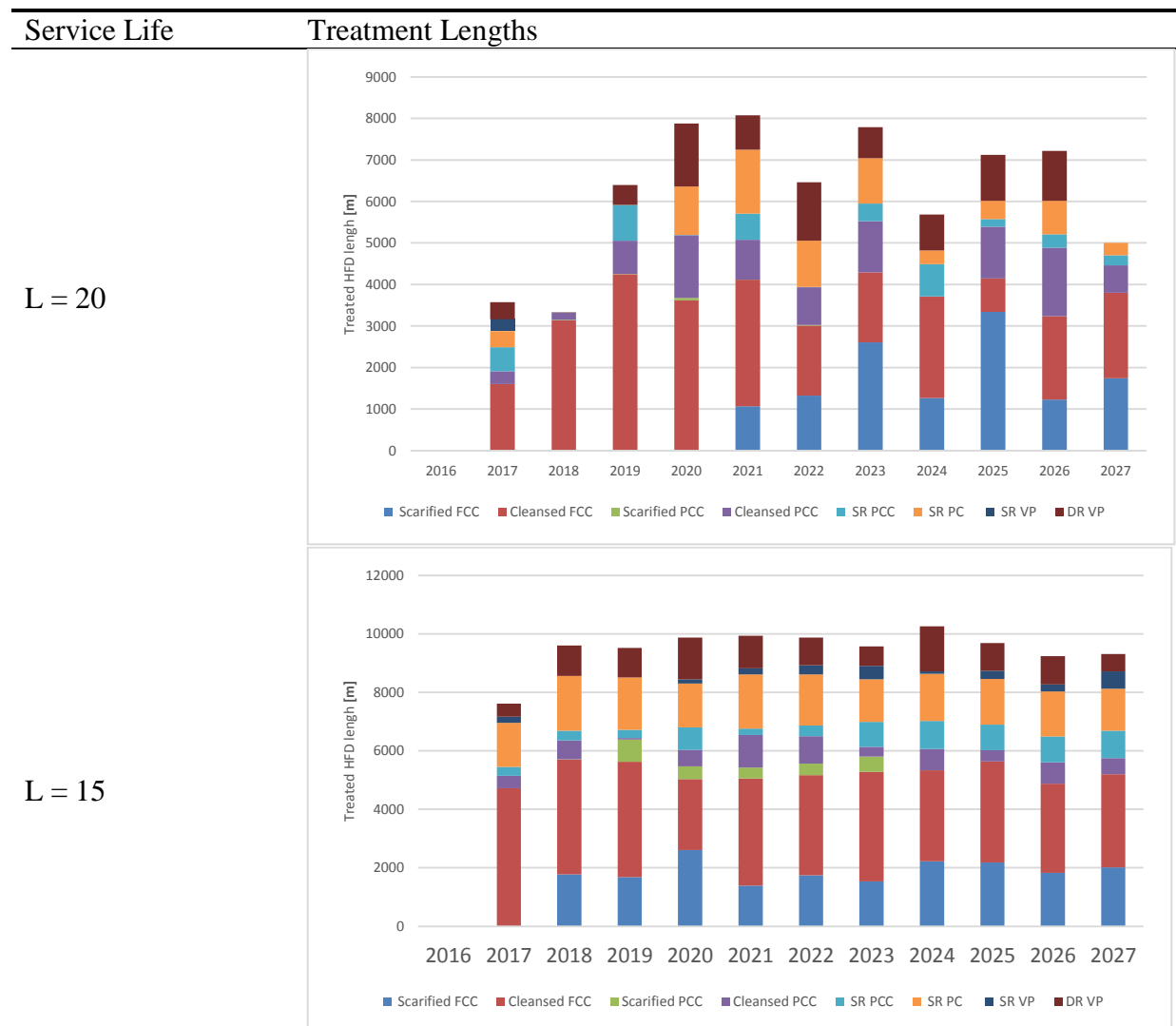


Table 12 Treatment Lengths exported from HFD DST

A more realistic maintenance strategy scenario was finally developed for CR using the DST. This was generated by adopting a more ‘representative’ condition breakdown of the HFD network across the A50 concession (Figure 35) to be compared with existing WLP long-term budget allocations. Deterioration projection was based on both service lives L=20, L=15 years and constraints were introduced in the model to limit the Very Poor, Poor Crusted, Fair

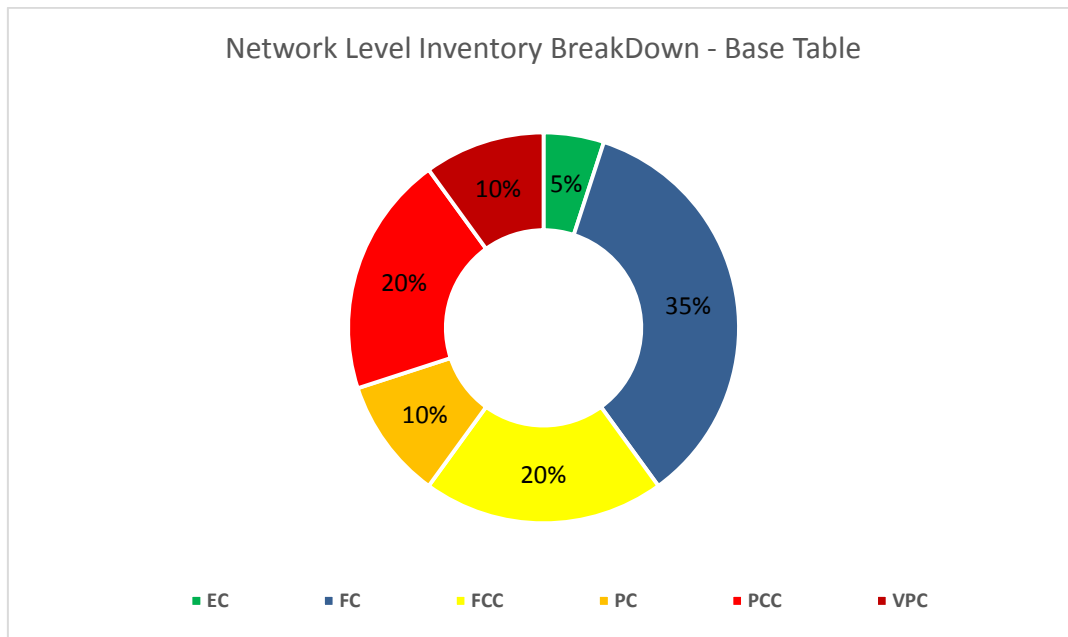


Figure 35 Condition Breakdown used for DST base table - A50 DBFO network

Crusted and Poor condition states; these can be seen in Figure 36. Different HFD length-limiting percentages are used here to represent in-service and handback criteria. Handback performance expectations are theoretically informed by O&M agreements; in the case of HFD with no quantitative (or even qualitative) standards available, the newly introduced model constraints aim to minimise HFD sections presenting extremely high risk of failure.

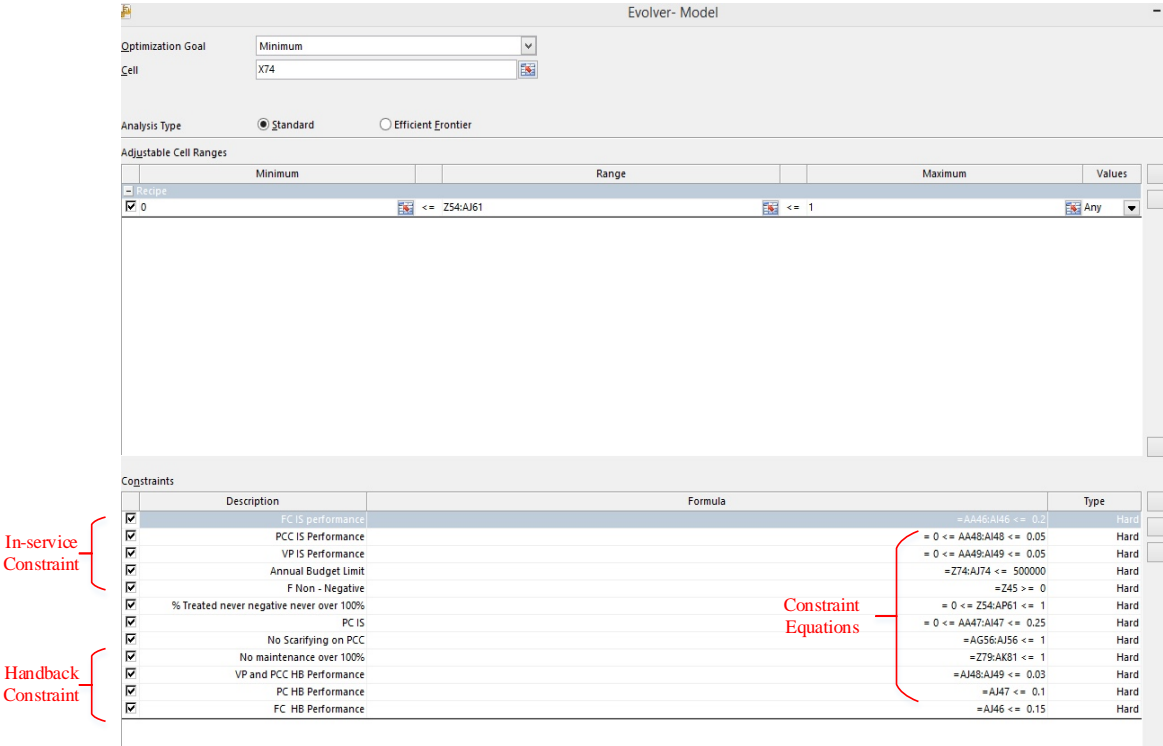


Figure 36 Definition of in service and handback constraints through excel add-in

The projected total maintenance spend is presented in Table 13. Figure 37 breaks down the annual spend requirement and performance at Handback (now factorising the more ‘strict’ constraints introduced in the analysis). The initial (2016) allocations are higher than the yearly average presented in Figure 37 due to the initially large lengths of deteriorated sections that require maintenance and rehabilitation. In a similar way the final year (2026) maintenance spend is high because of the strict handback constraints that limit the Very Poor and Poor Crusted lengths to 3% of the network. This approach enabled the development of best and worst – case scenarios (comparison of short and longer service lives) and the development of long – term maintenance strategies to be embedded with concession whole life plans.

Service Life	Total Maintenance Spend
L = 20	£1,031,158
L = 15	£1,269,822

Table 13 Maintenance spend as a function of service life

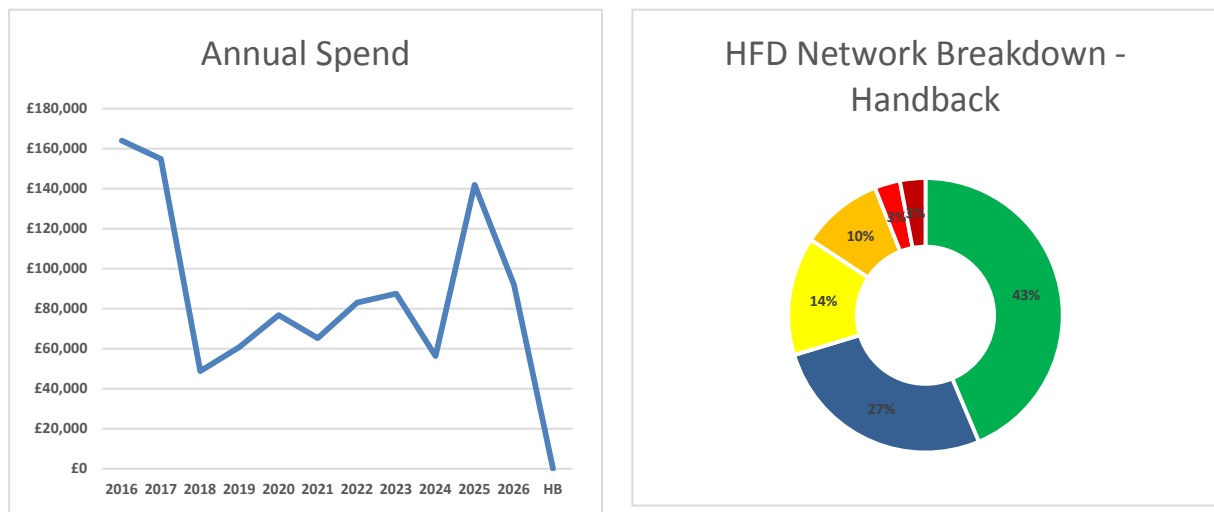


Figure 37 Annual Spend and performance at Handback adopting $L = 20$ years

4.4 SUMMARY

This chapter presented the detailed work undertaken in line with the project aim and objectives and individual research tasks described in Chapter 3. Conclusions further recommendations and the research impact are discussed in Chapter 5.

5 FINDINGS & IMPLICATIONS

5.1 INTRODUCTION

This chapter provides an overview of key findings of the research work aligned to the project's aim and objectives. An evaluation of the impact of the research mapped against the sponsor's objectives is also described while the potential impact on the wider industry and academic community is presented. Finally, a critical evaluation of the study leading to future research opportunities and recommendations is detailed.

5.2 THE KEY FINDINGS OF THE RESEARCH

For prolonged periods HFDs have been designed, built and managed without any integrated holistic strategy to inform long-term maintenance requirements being considered before. A number of factors have led to short-term reactive management approaches and the presented literature (Chapter 2) highlights how existing standards and practices tend to be overly generic and descriptive. What this work communicates is how this reactive thinking eventually leads to increased maintenance requirements, unexpected failures and potentially significant hazards for road users. Essentially a 'fire-fighting' maintenance approach restricts any type of forward planning and forces asset custodians to inevitably guesstimate current maintenance needs and projected rehabilitation priorities.

Research tasks developed to tackle the current maintenance thinking are described in Chapter 2. Academic publications over the four-year period, linked to the work-packages and outputs (presented in Chapter 4), detail a number of key findings that are further discussed in the following sections. Key conclusions from each research package can be summarised as follows:

- Inventory information is required to develop an asset information database. This can be initially based on HFD lengths and locations for a network level planning toolkit.
- Visual surveys adopting the proposed assessment guide (condition bands ranging from Excellent to Very poor) should be adopted to establish a network level breakdown of conditions and enable a targeted (if required) in-depth assessment of drains (using GPR and intrusive testing).
- GPR can be adopted for condition assessment if coupled with trial holes and data validation.
- At the project level, intrusive testing and calculation of condition indices to classify aggregate condition enables a detailed evaluation of HFDs and engineered scheme selection.
- Markov Chains and Transition Probability Matrices is a feasible solution to project deterioration at the network level. This enables the establishment of strategic future investment requirements.
- Adopting three proposed service life projections (using engineering judgement and network knowledge), various DST outputs can be established simulating variable deterioration profiles. This can be adopted to simulate different risk profiles.
- Service life and levels of service of HFDs surpasses the reported projection on c. 10 years.

Detailed discussion of the results and findings for each research work package (linked to stated project objectives) are provided in the papers in Appendices A to D and are discussed in the following sections.

5.2.1 INVENTORY INFORMATION

Central to Asset Management Systems are databases that define and describe the asset portfolio in a manner that enables asset custodians to generate a representative and holistic ‘picture’ of all assets managed in a DBFO portfolio. In regards to inventory data, the work has identified the need to build representative databases that hold HFD information at either (or both) the network and project level. At the moment, Connect Roads holds no such inventories and an exercise to collate the information for the A50 DBFO was undertaken. From this exercise (results described in Section 4.3.3), typical requirements for the final database were generated linked to either the project or network level as shown below:

- Network level structure:
 - Total Length of HFD trenches in road network
 - Types of Material primarily used in construction
 - Average width / depth of trenches
- Project level structure:
 - Location Referencing (mapped to HAPMS sectioning) also differentiating between carriageway verge or central reservation
 - Detailed information in regards to backfill material and presence of geotextile in trench
 - Detailed depth and width of trench extracted from as built-drawings (when available) or truth holes

Depending on the structure and form of the support tool to be developed, inventory data can form part of a larger asset database (e.g. Connect’s pavement inventory) or be defined and formulated in excel spreadsheets or a GIS database. For this work, an excel based spreadsheet was used (Section 4.3.6 and Paper 2 Appendix B). The collation of data can in theory be

completed using drainage as – built drawings; in hindsight, the lack of a complete set of drawings led to visual walkovers and site truth holes being undertaken. A detailed project level inventory design will be a key requirement for full integration of HFD to Connect’s pavement management IT module.

5.2.2 CONDITION DIAGNOSIS

Section 4.3 presents all condition evaluation elements developed to support the Maintenance Management system proposed. Where condition information and condition data collection methodologies for other key highway assets are defined, structured and embedded with existing management modules, HFDs have not been addressed in the past in a manner that reinforces AM principles and supports engineered investment planning. The work has defined a series of condition evaluation approaches based on three different assessment methods:

- Visual Network Level
- Detailed Destructive sampling and sieving (truth holes)
- Non Destructive Testing (GPR)

Each approach has its own merits and limitations (discussed in Paper 2 Appendix B Section 2.3.2 Managing Drainage Assets: The Bottom-Up Options, Paper 3 Section 2.1 HFD Function, Deterioration And Condition Assessment Principles; Defining The Basis For Engineered Maintenance Planning and detailed in Section 4.3.4). Visual surveys can be formalised and structured for fast and relatively cost-efficient data extraction and if embedded with condition data collection annual cycles, they can become a robust information source. This though can be more fitting for network level budget formulation and requires a number of assumptions to be made in regards to deterioration extent in the basal parts of the HFD trench. The research output defines and describes condition bands to be embedded in visual assessment protocol to control subjectivity and bias in data collection.

Truth holes and sampling / sieving is perhaps the most accurate and objective approach to condition evaluation. It is also an extremely disruptive and slow process. With no prior work available to date, the research work has drawn from relevant ballast evaluation studies (discussed in detail in Paper 4 – Appendix D Sections 3 – Experimental Study and 4 - Conclusions) and has presented a number of condition metrics that can be used to inform asset custodians about anticipated deterioration levels and performance drop (extrapolated from large-scale permeability trials as exhibited in Paper 1 Section 3 - Experimental study and further enhanced and discussed in Paper 3 Section 3.1 What to measure; fouling scales and drainage capacity). The use of window samplers that has been trialled on the A50 DBFO network may yield satisfactory results and minimise sample collection errors. The approach can also be applied to control the amount of aggregate removed from a trench while offering the option of classifying fouling extent for near undisturbed samples.

With machine - based data collection methodologies being key information sources for pavement assessment, an exploratory study of GPR data collection and processing routines for HFDs has been presented (introduced in Paper 3 – Appendix C and enhanced in Paper 4 – Appendix D). The two academic papers produced discuss theoretical background, laboratory trials and applications used to adopt the NDT technology. From these a number of conclusions can be raised about the application of the non-destructive technique for HFD assessment. These include:

- A linear relation can be extracted to link the incremental increase of ϵ as a function of R_{FV} (or any other fouling index used to classify HFD condition) in an artificially fouled sample (presented in Paper 3 – Appendix C). In simple terms, propagation characteristics of the EM wave through fresh and fouled samples can be used to infer back to a condition state. By building up libraries depicting ϵ as a function of fouling

extent, advanced post-processing methods (scattering from voids) can become more accurate.

- Water has a large impact on GPR condition surveys; the combination of water and fouling can be challenging to classify hence truth holes should be employed on site during data collection exercises. The analysis of representative samples should be completed prior to GPR data processing to allow appraisal of the EM response of the evaluated trenches. This effect is discussed in Papers 2 and 4 where application of GPR processing options are discussed in detail.
- Different antenna configurations, backfill material or fouling types (composition) will affect EM material properties. When GPR studies are to be procured on site calibration exercises should be presented to asset custodians to supplement processed data.
- Void scattering can be used to infer back to available void space in a trench; the approach can be adopted for condition surveys but comes with limitations. Moisture in a trench limits wave penetration; ideally data collection should be avoided under wet site conditions.
- 1 GhZ antennae have shown promising results in regards to void scattering for Type B aggregate material. Scattering events were not visible using lower frequencies. In contrast higher frequency antennae (2 GhZ) may be more appropriate for data extraction but wave penetration in a trench will be limited.
- Field studies targeting void scattering should be planned in a way that scattering from ‘fresh’ trenches can be used as baseline. Combined with truth holes this can make the assessment of long HFD stretches more representative and objective.

- GPR surveys still require Traffic Management. Depending on site availability and practicalities a few kilometres per shift can reasonably be surveyed. Full network coverage will probably be a staged process to avoid excessive traffic management costs.

5.2.3 CONDITION PROGNOSIS AND DECISION SUPPORT TOOLS

A probabilistic deterioration approach was developed to enable HFD long term modelling and maintenance planning as discussed in Paper 2 (see Appendix B Section 3.5.2 Discrete Condition States: Defining The Boundaries And Embedding Maintenance Activities) and presented in detail in Section 4.3.5. The approach was based on network level visual surveys undertaken on the A50 DBFO network. The six condition bands used were proposed after evaluating HFD deterioration mechanisms and assessing past maintenance records and sampling from various networks. A number of conclusions can be drawn from the various work-packages associated with the Condition Diagnosis elements of the maintenance management framework proposed. Key points include:

- Service life projections generally communicated in the industry of approximately five to ten years are largely understating actual site conditions if used together with a transition probability matrix. 15 and 20 years have been used in the analysis and yield satisfactory results. Comparisons are discussed in Section 4.3.5 and an example and further discussion presented in Paper 2 – Appendix B .
- Different failure modes associated with surface crusting (top down failure) and basal sedimentation (bottom up) have to be considered to build HFD ageing / renewal rules. This will enable better short and long term planning and allocation of maintenance budgets according to actual deterioration profiles. The failure modes are first discussed in Paper 1 (see Appendix A Section 2.1 Deterioration and Maintenance)

and further expanded upon and implemented in analysis throughout the work. They are also integrated in condition bands in Paper 2 – Appendix B (Section 3.5.2 discrete condition states: defining the boundaries and embedding maintenance activities) and subsequently implemented in the Decision Support Tool presented in Section 4.3.6.

- Markov chains can be used to predict network level condition breakdown. In the proposed state, deterioration is largely based on network-experience and iterations using range of representative service lives. Continuation of data collection can upgrade the transition probabilities used and increase objective modelling and accurate representation of site conditions. The probabilistic approach is presented in Section 4.3.5 and Section 4.3.6 where it is integrated in the proposed Decision Support Tool.
- Strategies and maintenance projection profiles can be generated adopting a cost-minimising objective function from an excel spreadsheet and by using optimisation add-ins. A simple add-in can enable performance tracking and the development of project specific serviceability constraints. The effect of introducing different budget levels can also be easily integrated in the analysis. This was first defined in Paper 2 (Appendix B) and further appraised in Section 4.3.6 where examples are presented.

5.3 IMPLICATIONS/IMPACT ON THE SPONSOR

The aim of this work was to develop the means, methods and systems to move Connect's HFD maintenance approach to a proactive philosophy. With contract handback fast approaching, the project sponsor is focusing on asset performance requirements and detailed Maintenance & Rehabilitation needs to meet contractually specified asset performance criteria. The research work proposed and adopted a series of Asset Management elements to

formalise a decision support tool capable of projecting maintenance needs over a planning horizon spanning to year 2026 (handback).

The project sponsor is now evaluating implementation of the DST across the five concessions and adoption and development of a Condition Assessment System that will integrate the three proposed assessment approaches (visual, destructive, non-destructive). The inventory generated for the A50 was collated from data available for the network level and future Asset Management tasks include a more detailed HFD investigation that should enable a detailed inventory to be generated and be fully embedded within Connect's pavement DST.

If the impact of the research output for the project sponsor could be summarised in three key points these would ideally be:

- Enabled CR to identify sources and types of HFD data that can produce value for CR.
- Enabled CR to establish data collection frameworks (take ownership of the data).
- Enabled CR to identify how HFD specific knowledge can be generated.

In regards to the A50 DBFO exercise, the probabilistic decision support tool suggests an investment requirement ranging between c. £1.0m to c.£1.3m. for maintenance operations. This projection was compared to existing concession WLPs, enabling Connect to re-evaluate its current position in terms of ancillary assets total maintenance allocations and to manage the re-profiling of annual budgets. Connect Roads benefits from the additional engineering condition evaluation elements embedded within the standard business as usual models for project level HFD assessment. Visual surveys undertaken (through the Operator as part of their pre-agreed condition data collection lump-sum) on intervals that will be defined in follow up discussions, will provide a cost-effective data collection process (and a normalised approach in visual based condition assessment). The cost for undertaking additional surveys (sampling, and GPR) aiming the detailed classification of the aggregate backfill, can initially

be estimated as a percentage of the total cost for the in-year volume of works (5-10% typically adopted for structures and pavement in existing CR's Whole Life Plans). In principle CR's aim is to build a sufficient condition database to project maintenance needs and meet handback conditions (justify maintenance up to handback) will drive the budget allocation for condition surveys in the following years.

On a secondary level, the probabilistic deterioration approach and excel based DST was used for pavement maintenance planning and prioritisation for the M77/GSO DBFO. The toolkit was rather simplistic in structure and outputs focused on network level planning but is currently being used to supplement existing pavement management IT systems and further enhance Lifecycle Plans. This was communicated with clients (Transport Scotland) and further embedment of the approach is pending for this particular DBFO project.

5.4 IMPLICATIONS/IMPACT ON WIDER INDUSTRY

The work undertaken over the four-year research period has raised a number of issues with HFD maintenance planning. With concession handback approaching for a number of PFI road projects across the UK, asset owners will need to address maintenance requirements, serviceability and residual life in a rational way.

The absence of clear quantitative means to assess performance (a fact that fundamentally drives this research project) across the industry and the typical cyclic / reactive maintenance thinking deployed to date has been restrictive in terms of maintenance forecasting. The research outputs develop a unifying platform through which a dialogue about Filter Drains can take place with external stakeholders. This will enable the evaluation of performance, serviceability, and of deterioration and handback criteria. The use of a condition driven maintenance planning methodology was built on the premise of a series of visual / intrusive / non-destructive asset assessment approaches. Condition survey requirements can now be

formulated to match CR's whole life planning strategies across concessions to allow renewal requirements to be defined prior to handback.

While the project focuses on the development of a strategic plan to achieve handback as defined in typical PFI contract documents (supported by the HFD Maintenance Management system that adheres to Asset Management principles), elements of this work can be adopted and further developed for use by asset custodians facing different service requirements (for example Local Councils) and adhere to risk or cyclic maintenance planning philosophies.

The drainage management guidance (HMEP, 2012a) suggests a linear condition data collection approach or a shift to a data collection hierarchy that radiates from local flooding hotspots (indicating higher risk for failure). Both options enable the development of a management information database to support future decision making. The guidance fails though to define assessment guides and how the physical performance of a drainage system can be evaluated in an engineered manner.

The work undertaken in the past four years allows for the integration of an engineered assessment methodology linked to asset performance (and subsequently remaining service life) to existing data collection strategies. This may enable asset custodians invested in a Time or Risk Based Maintenance Planning approach to re-evaluate and enhance their current strategic planning and develop assessment and deterioration projection protocols that fit in-situ asset ageing patterns. In principle, while the work doesn't address a risk based data collection approach or a flooding risk evaluation primarily due to a condition driven handback framework for asset classes in PFI projects, outputs can reinforce the case of engineered investment planning by supporting a number of recommendations offered in the drainage management guidance document.

Throughout the project in addition to the academic papers (Appendices A to D), research findings were publicised or discussed with various third parties. A list is summarised on Table

14. The GPR work and the adoption of innovative data processing techniques also led to the securement of an EPSRC Bursary for an undergraduate project for a Loughborough University student (Frequency Domain Evaluation of GPR Signals for Infrastructure Asset Condition Investigation).

Table 14 Research findings publicised to wider industry

Presentation / Paper Title	Stakeholder / Event	Year
Highway filter drains maintenance management	Innovation & Research Focus ICE / Paper	2014
Maintenance of Highway Filter Drains (research update)	Highways England / Presentation	2014
Condition indices, condition evaluation and data-driven decision making for highway filter drains	Innovation & Research Focus ICE / Paper	2015
Infrastructure Asset Management	Loughborough University / Lecture	2015 & 2016
GPR application for HFD condition evaluation	COST Action / Poster Presentation	2015
Maintenance planning and performance evaluation of HFDs	Balfour Beatty - Vinci / M5 Smart motorway scheme	2016
HFD condition diagnosis and condition prognosis	Transport Scotland / Presentation	2016
Asset Management; the way forward	Connect Roads Strategy Forum	2016
Data, Information and Knowledge: Condition Driven Maintenance for HFDs	Chartered Institute of Highways and Transportation / COLAS competition	2016
Condition Driven Maintenance Management of Highway Filter Drains	Chartered Institute of Highway and Transportation / Lecture	2016
Investigation of Filter Drain sections / A50	Site evaluation / CR	2016
Highway Filter Drains – Monitoring, Modelling and Maintenance Planning	University of Nottingham / Lecture	2017

5.5 RECOMMENDATIONS FOR FURTHER RESEARCH

Throughout the four-year research project, three key themes that merit further research were discussed with various parties:

- GPR post-processing options

Throughout the work, material property extraction and analysis from void scattering were primarily employed to study and evaluate HFD condition. The approach has a number of limitations, moisture content being one of them. In an effort to tackle the issue,

the adoption of a different post-processing approach (evaluation of frequency domain of the EM signal) was evaluated. A short study was therefore developed that would eventually support an EPSRC student bursary for a project dealing with frequency evaluation of the GPR signal.

With only limited research related to such data interpretation from GPR available, further work can enable the better understanding of an ‘uncharted’ area of GPR data processing and interpretation and will possibly enable condition evaluation approaches to be more realistic and effects of water content better understood. The topic could link primarily to work on highway drainage systems but is also directly relevant to railway track-bed and pavement condition assessment.

- Maintenance and rehabilitation options

The project was primarily focused on defining and developing the means to proactively manage HFDs across Connect’s asset portfolio. Within the proposed ageing / renewal rules maintenance impacts were correlated to existing rehabilitation techniques available to the wider industry. In recent years, a few maintenance and renewal options have been growing in popularity across the UK roads network and these relate to in-situ aggregate recycling. Such options are though still expensive solutions.

CR has engaged with various parties offering drainage maintenance solutions and trials are planned to be undertaken in the near future. The effect of these innovative solutions will be monitored and evaluated.

- Innovative HFD Design

The evaluation of filter drain sections across Connect’s five DBFO concessions reveals a number of inherent HFD design limitations; it would financially perhaps make more sense to minimise sedimentation at the uppermost of the drainage trench and target its

replacement when fouling exceeds acceptable levels. This suggests the adoption of a sacrificial layer that may require more frequent interventions but will limit excessive aggregate replacement in the long run therefore reducing overall Life Cycle expenditure.

Currently there is limited awareness of ‘project-spanning’ maintenance requirements for this type of drainage solution. It also seems that HFDs have become part of roads’ ‘buried infrastructure’; if the problem cannot be seen then it is not a problem. In truth this applies to a number of ancillary assets (often to structural components of bridges too) and future maintenance requirements are often guesstimated.

With scarce financial resources and ever increasing renewal and rehabilitation needs, the roads industry has shifted its focus to Asset Management principles. This paradigm shift integrates all phases of an asset’s service life to long term planning. A key phase in this process is in fact design and construction. It would thus make sense (factorising AM thinking) to focus on design for maintenance and renewal principles rather than design for failure. An investigation of different long-term HFD design options should be evaluated (different materials, use of geotextile, and adoption of sacrificial layers) and this should be integrated in the design process to enable engineered and rational maintenance cost projections.

5.6 CRITICAL EVALUATION OF THE RESEARCH

The four-year research project was designed to meet Connect Roads’ internal Asset Management requirements and to align the proposed system with the sponsor’s existing pavement management understanding. The focus of the work was thus mainly targeting the development of a decision support tool that can be readily adopted for maintenance cost projection and network-level strategy development. The primary aim of this project was thus met as CR is now capable of undertaking condition investigation studies aligned to the

physical condition of the asset while being able to project deterioration and maintenance investment requirements to meet Handback criteria.

A number of challenges were encountered through the process and these usually relate to how such a system can be practical and feasible in terms of both incurred costs and ease of application. Throughout the work, the multi-faceted AM objective had to be tackled at both the strategic and operational or tactical levels. A strategy for HFD maintenance management had to be defined however at the same time the tools and technologies to enable the integration of this strategy in CR's business models had to be developed and tested. In various scenarios to achieve the transition to Asset Management principles (condition evaluation, performance measurements, modelling), 'off-the-shelf' solutions were used. This is evident throughout the Non-Destructive Testing and Decision Support Tool building work-packages. The availability of GPR systems was hence limiting data processing options, and current decision support tools used by Connect were 'dictating' the project's general course of action. This research work was of course not one aiming to re-define and re-develop GPR data post-processing techniques or one focusing on multi-objective optimisation algorithms. It was instead a presentation of all the means required to achieve a proactive MM framework for a drainage asset that has been managed in a 'run to failure' philosophy. It may thus articulate the AM proof of concept but in hindsight, elements and work-packages throughout the four-year cycle could benefit from additional academic consideration and further development.

The application of all research methodologies in this thesis factorises often-conflicting state of the art and state of practice expectations. Evidence of a number of outputs has been peer-reviewed and this supports the rigorous academic nature of the methodology adopted. A broad industrial adoption of the proposed management frameworks and tools remains to be assessed.

In essence, this thesis addresses what should be achieved to minimise reactive and ‘fire-fighting’ maintenance approaches for filter drains across a road network. This is derived from current Asset Management elements which are in principal universal and break down what data needs to be collected and what internal processes should be developed. The discussed set of tools, technologies and methods to be integrated in this system to support the defined objectives are tailored to CR’s internal Asset Management culture and can be modified for a different asset custodian if the same objectives can be met. From Connect’s perspective, the developed methodology will enable an engineered discussion with project clients (Highways England, Transport Scotland) and with external collaborators to formalise and initiate contractual handback processes.

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APPENDIX A ASSESSMENT OF HIGHWAY FILTER DRAIN FOULING AND PERFORMANCE CONSIDERATION (PAPER 1)

Full Reference

STYLIANIDES, T., FROST, M., FLEMING, P., ELJABER, A. & MAGEEAN, M. Assessment of Highway Filter Drain Fouling and Performance Considerations. Transportation Research Board 94th Annual Meeting, 2015

Abstract

The road carriageway and pavement sub-surface of many UK highways are drained by Highway Filter Drains (HFD). These are gravel filled trenches fitted with a porous carrier pipe at the base that conveys surface and sub-surface water to an outfall. HFD are typically characterized as free draining upon construction however, over time the voids of the granular medium become filled due to the intrusion of fines washed from the adjacent earthworks or pavement surface. The lack of understanding of the deterioration mechanisms and the absence of a structured fouling characterization limit the assessment of operational and residual HFD life to qualitative or subjective estimation of in-service performance. This extends to maintenance procedures that are predominately reactive. This paper reviews the current state of knowledge of HFD performance and drainage media condition assessment. It then presents a method of fouling characterization based on assessment of samples from in service drains. Three fouling scales are thus suggested; the percentage drain fouling, the foulant-aggregate ratio and the free voids ratio. In-service HFD are found to be functioning at an acceptable standard with a limited number of localized failures attributed to highly fouled layers at the surface of the trench. It is proposed that a rational evaluation of a HFD section should employ means other than just visual indicators. The fouling assessment is linked to laboratory permeability tests conducted with different levels of filter material fouling. It is found that the extent, spreading and type of fouling are important to determine how the filter aggregate performs.

Paper type – Peer Reviewed Conference Paper

1 INTRODUCTION

Highway Filter Drains have been used in the United Kingdom for considerable time to drain lengths of the highway network. These are aggregate filled trenches fitted with a porous carrier pipe at the base to remove surface and sub-surface water from the pavement system. The granular material used (typically exposed to the surface under most UK construction configurations) allows for efficient removal of pavement run-off due to its highly porous nature. It also enables the removal of water that finds its way into the pavement foundation and structural layers. Filter drains have a number of inherent limitations; most importantly they have a finite operational life due to the reduction of free voids space as road detritus and other introduced fines enter the filter trench restricting the free flow of run-off. (1).

Currently there are limited management systems to monitor the performance of filter drains with maintenance approaches being mainly reactive, based on dealing with areas of failed drainage where they occur (evidenced by pavement flooding), or by periodic maintenance. This paper, as part of ongoing research aiming to present a holistic HFD Maintenance Management system, presents a suggested way forward to allow a quantitative assessment of HFD by evaluating a fouling characterization methodology of the drains (based on similar approaches used for railway ballast), mapped against laboratory permeability assessment of filter drain material as it blocks. HFD are introduced and maintenance thinking, performance and capacity failures are addressed. The paper then presents the fouling characterization thinking used to assess the performance of railway ballast, and suggests how a similar approach could be used for HFD. Fouling scales are subsequently suggested from field and laboratory data, comparing the in-situ condition of filter drain media to laboratory assessment of hydraulic performance.

2 BACKGROUND

A general definition of Highway Filter Drains is provided in (2) as ‘A drain constructed using permeable materials which allow the entry of water whilst retaining the surrounding material’. HFD consist of gravel filled trench with a porous carrier pipe at the base. Frequently a geotextile is provided on the external faces and/or near the surface of the trench.

The drains are installed in verges and/or central reservations adjacent to low edges of pavements allowing surface water to run off the pavement (or from adjacent earthworks) directly into the trench and permeate through the stone aggregate to the porous carrier pipe at the bottom. The geotextile is used to prevent the entry of fines carried into the trench by either surface or sub-surface water ensuring the drain is kept clear to provide a free-draining path throughout its length.

The gravel used has a porous nature that enables rapid removal of water. Pipe diameters used are usually relatively large (up to 375mm), there is, therefore also a large capacity to intercept groundwater. This can act as a cut-off to below the pavement foundation capping-layer (3).

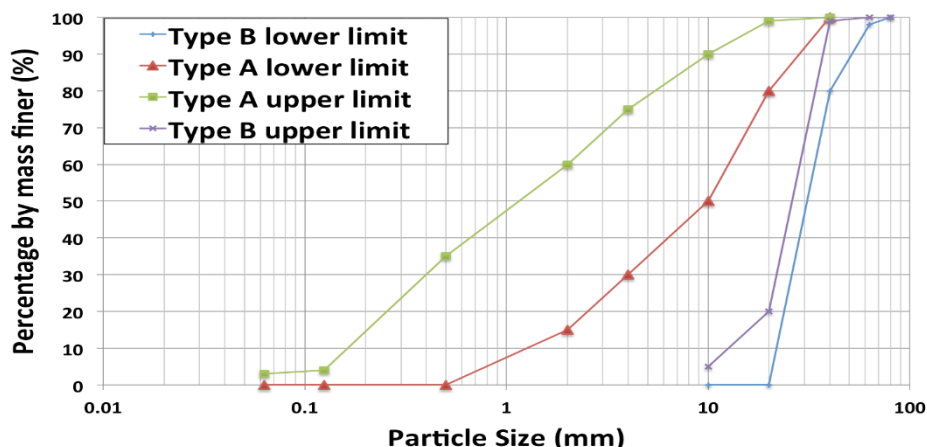


FIGURE 1 Gradation Envelopes For Type A And Type B Adopted In Highway Filter Drains.

(4) specifies two broad granular material gradings for aggregate used in the drains as Type A and B (Figure 2), Type A being a finer material. Type A is selected as a balancing option between permeability and filtration of surface foulants, Type B offers higher permeability (5-6). The different granular fills therefore offer different water removal efficiency and hence present different forms of functional failures (Type A is more prone to fouling accumulation near the surface layers).

2.1 DETERIORATION AND MAINTENANCE

Filter drain fouling is the term used to describe the filling of voids and the gradual clogging of a filter drain trench. This occurs due to the collection of detritus (foulants) being washed into the drain from pavement run-off or infiltration of fine particles from adjacent earthworks resulting in the reduced performance of the drains. Currently there are no standards or guidance to evaluate the level of performance against a quantified level of HFD fouling. However, in some long-term maintenance contracts there is a specified minimum level of permeability performance at their beginning and a minimum requirement for residual life at their end. The justification for these values is not included in the available literature.

Current UK design guidance and empirical experience suggest that highway filter drains should achieve an operational life of approximately 10 years. The filter material is expected at this point to require replacement or recycling, and this is often included in maintenance plans. However, during filter drain field evaluations (5-7) acceptable performance of many drains has been observed after 20 years of operation with minimal or no maintenance undertaken. Studies (6) have shown there's a differentiation between the service life of Type A and Type B drain aggregate and an implied correlation between aggregate type and modes of failure.

As standard practice, the performance of the drains can be assessed by visual inspection of the surface of the drainage trench (8) resulting in reactive or periodic routine maintenance. The reactive approach results in a number of disruptive performance failure events (i.e. highway surface flooding and/or possible premature pavement failures (7,9,10)) while a time based remedial regime, dependent on the frequency of cleaning, reduces the risk of flooding but inevitably specifies cleaning where it is not actually required. Visual indicators of the failure include surface ponding of water or siltation, vegetation growth and visible wheel rutting at the surface (8). These are usually an indication of large detritus depositions near the surface of the trench. However, water ponding can also be the result of large fouling levels concentrated

deeper in the drain. Current UK HFD maintenance practice is broadly limited to three remedial options.

- Removing and replacing the material,
- In-situ aggregate recycling and re-use (10),
- Scarifying of the trench (loosening the aggregate / detritus cake that accumulates at the surface of the trench).

2.2 RAILWAY BALLAST CONDITION EVALUATION

Railway Ballast is composed of uniformly graded angular aggregate that becomes progressively fouled by ingress of foreign particles from the track surface, subgrade infiltration, or fines generated from track/ballast mechanical wear during cycling loading (12). Both railway ballast and filter drains are designed using materials that are highly porous, however their deterioration mechanisms and characteristics required are different as they are generally designed targeting a different operation context (for ballast mainly load related stability, though good drainage is also required). Ballast condition and performance evaluation is based on determining and quantifying the levels of fouling (13) and this approach offers a potential way forward for filter drain fouling assessment.

2.2.1 BALLAST FOULING MEASUREMENTS

Research has been carried out to correlate ballast-fouling levels to universal fouling scales that can be used for performance monitoring and evaluation. These scales are derived using mass or volume based methods (14). Such indices comprise a simple method to correlate particle size distributions to a fouling status that can be applied as an indicator of fouling levels and subsequently performance. Typically for ballast the fouling material is defined as the fraction of particles passing the 9.5mm sieve representing the particle matrix that is expected to infiltrate the ballast sections or be generated due to wear and mechanical breakdown (12). This is based on gradation requirements and may differ in railway systems in different areas (15).

2.2.1.1 MASS BASED INDICES

Selig and Waters (12) proposed the Fouling Index (FI) as a means to classify fouling based on grading from representative samples of ballast.

$$FI = P_{\%4.75mm} + P_{\%0.075mm} \quad (1)$$

Where:-

- $P_{\%4.75mm}$ = Percentage by mass passing the 4.75mm sieve, and
- $P_{\%0.075mm}$ = Percentage by mass passing the 0.075mm sieve.

By using the $P_{\%0.075mm}$ in the equation, the importance of finer fractions is highlighted. These fractions, which are expected to have a large impact on the performance of the ballast section due to their inherent lower hydraulic conductivity properties, are also included in the $P_{\%4.75mm}$ parameter and thus slit/clay fractions are summed twice in the FI .

2.2.1.2 VOLUME BASED INDICES

The percentage void contamination (PVC) is defined in (16) as the ratio of the volume of re-compacted fouling material to the volume of the free voids of the ballast

$$PVC = \frac{V_f}{V_{vb}} \% \quad (2)$$

Where:-

- V_f = Recompacted volume of material passing the 9.5mm sieve
- V_{vb} = Volume of voids extracted by material retained at 9.5mm.

To quantify fouling within ballast layers the Void Contaminant Index (VCI) has also been proposed (17). As with the PVC , the VCI establishes a volumetric classification of fouling levels. The difference between PVC and VCI is based on the method used to extract each index. For PVC , a laboratory approach is followed; the VCI requires a field procedure to obtain the parameters used in the index.

$$VCI = \frac{V_{f1}}{V_{vb}} \% = \frac{(1+e_f)}{e_b} \times \frac{G_{sb}}{G_{sf}} \times \frac{M_f}{M_b} \times 100 \quad (3)$$

Where:-

- V_{f1} = 'actual' volume of fouling material,
- V_{vb} = volume of voids in fresh ballast,
- e_b = void ratio of fresh ballast,
- e_f = void ratio of fouling material,
- G_{sb}, G_{sf} = specific gravity of fresh ballast and fouling material respectively, and
- M_b, M_f = dry mass of fresh ballast and fouling material respectively.

Grading based indices are solely based on sampling and sorting; they may though lead to inconsistent representation of fouling levels; both FI and PF fail to differentiate between different types of foulant. This is particularly important in ballast evaluation studies due to the presence of different sources of fouling (12, 16).

2.2.2 LARGE SCALE PERMEABILITY TESTS

The condition and performance evaluation of railway ballast often extends to drainage performance and how finer fractions of foulant are expected to affect drainage. A number of

large-scale constant head permeability studies have thus been conducted on ballast (16-19). In these studies foulants that simulate in-service track deterioration have been used to extract an inferred relationship between a fouling scale and hydraulic conductivity. While the testing methodology and apparatus used may vary, the objectives of these studies are similar. The hydraulic conductivity of the ballast reduces with increasing fouling levels converging eventually to the conductivity of the foulant itself (17).

3 FILTER DRAIN FOULING EVALUATION AND ON CONDITION MAINTENANCE

By using standard rules for treatment selection and established intervention levels inferred from measured performance, a consistent approach could be utilised to specify works across the HFD network. The adoption of such rules should eradicate under or over (reactive / periodic) maintenance of the highway asset and ensure acceptable performance throughout its operational life based on predictive and preventive approaches.

To move to a proactive maintenance management system, the case of railway ballast maintenance management has been presented where a structured condition assessment hierarchy is used that addresses the evaluation of fouling concentrations within the ballast layers and integrates hydraulic performance and ‘drainability’ within the evaluation process.

As described above, visually assessing filter drains can be a quick evaluation approach. In practice though, only a limited amount of information can be extracted from this, potentially leading to unexpected drainage failures or unjustified maintenance interventions. Based on the rail approach, evaluating fouling levels for in situ drains and establishing performance boundaries using hydraulic testing offers a more rational approach.

The following section presents work from a field and laboratory study to evaluate and quantify the levels of fouling within in-service HFD and, to investigate the impact of fouling on the effective ‘drainability’ of the material. Condition assessment and performance evaluation are presented here as precursors to determine the optimal level and type of maintenance that should be carried out to ensure HFD operate at the standard of service required.

3.1 HFD FOULING CLASSIFICATION AND FOULING SCALES

The key challenge in evaluating HFD fouling is to establish a fouling scale that reflects the influence of the fouling material, yet can be easily attained to characterise the condition of the drain. Three fouling indices are thus proposed for filter drain condition evaluation. The concepts developed for filter drains are derived using the specified HFD aggregate grading requirements (Figure 1).

A mass based index is suggested, namely the Percentage Drain Fouling (PDF). The formula includes the 10mm size sieve as the aggregate size cut-off that signifies the fouling material concentrations within the sample. This originates on the minimum particle size anticipated to be used in a 20/40 aggregate material in filter drains (Type B). All particles extracted by sampling and grading below the 10mm boundary are assumed to form the introduced foulant particle matrix. The 0.063mm size sieve is also used to highlight the anticipated increased weight of fines’ concentration on the overall permeability of the section, based on the silt/clay fraction. In addition, two volumetric scales are developed; the first as the ratio of the solid

volume of foulant to the solid volume of aggregate and the second as a quantification of the free voids space in the sample. The later is established by estimating the available void space within a 'fresh' Type B sample (which is expected to remain constant for the Type B aggregate but to vary if different types of aggregate are used as backfill) and the volume of the introduced material by extracting a representative sample and the basic material properties of the backfill and foulants (namely specific gravity and voids ratio).

Percentage drain fouling (PDF) Based on material grading.

$$P_{DF} = P_{\%10mm} + P_{\%0.063mm} \quad (4)$$

Where:-

- $P_{\%10mm}$ = Percentage by mass passing the 10mm sieve (as fouling material)
- $P_{\%0.063mm}$ = Percentage by mass passing the 0.063mm sieve.

Foulant - aggregate ratio (R_{F-A}) Based on calculating the ratio of the solid volume of foulants to the solid volume of aggregate (material retained at the 10mm sieve size after grading). This index requires the extraction of the specific gravity parameter of both aggregate and fouling material.

$$R_{F-A} = \frac{V_F}{V_A} = \frac{M_F}{M_A} \times \frac{G_{SA}}{G_{Sf}} \quad (5)$$

Where: -

- V_F, V_A = volume of fouling and aggregate respectively,
- M_F, M_A = Mass of fouling and aggregate respectively, and
- G_{Sf}, G_{SA} the specific gravity of fouling and aggregate materials.

Free-voids ratio (R_{FV}): Based on calculating the ratio of the volume of free voids of the in-service back-fill (voids of fresh material – volume of fouling) to the volume of free voids of fresh material.

$$R_{FV} = \frac{V_{VFRA} - V_F}{V_{VFRA}} = \frac{e_{fr}V_A - \frac{M_F}{G_f}}{e_{fr}V_A} = \frac{e_{fr}\frac{M_A}{G_A} - \frac{M_F}{G_f}}{e_{fr}\frac{M_A}{G_A}} \quad (6)$$

Where:-

- V_{VFRA} = Volume of voids in fresh aggregate,
- e_{fr} = Void ratio of fresh aggregate.

3.2 DESIGN OF EXPERIMENTS, MATERIALS AND METHODOLOGY

3.2.1 FIELD EVALUATION SAMPLING AND SORTING

To study the extent of filter drain fouling, studies of in-service drains were conducted on five locations on a selected highway section. The objectives of the study were to identify and characterize the foulant and fouling concentrations within the filter drain trenches and

subsequently to correlate these to an engineered fouling status as a means of performance characterization.

The trenches in this study were constructed in 2003 using Type B material as backfill and a larger (up to 75mm nominal size) aggregate as trench top-up; design information for the drains indicated that a geotextile layer should have been provided at a depth of 300mm (below the top-up material); this was not observed during excavation but a geotextile was found at a depth of about 1m. It is assumed that during their life these drains will permit free vertical flow of runoff and detritus will enter the system and will be retained at the geofabric deeper in the trench. The minimum permeability requirement for these drains upon construction was established at 6 mm/sec.

Trial holes were extracted on the carriageway verge in the drain at each location (named holes A to E); as material was removed layer by layer (approximately 300mm per layer, up to a predefined depth of 1m), an initial visual assessment of fouling levels was made. At two locations (C and D) the excavation depth reached the geofabric located 1m deep in the drain. It should be noted that trial holes and sample extraction were limited due to severe weather conditions and reduced visibility (locations A and B). Samples from each point were collected and taken to the laboratory for further analysis.

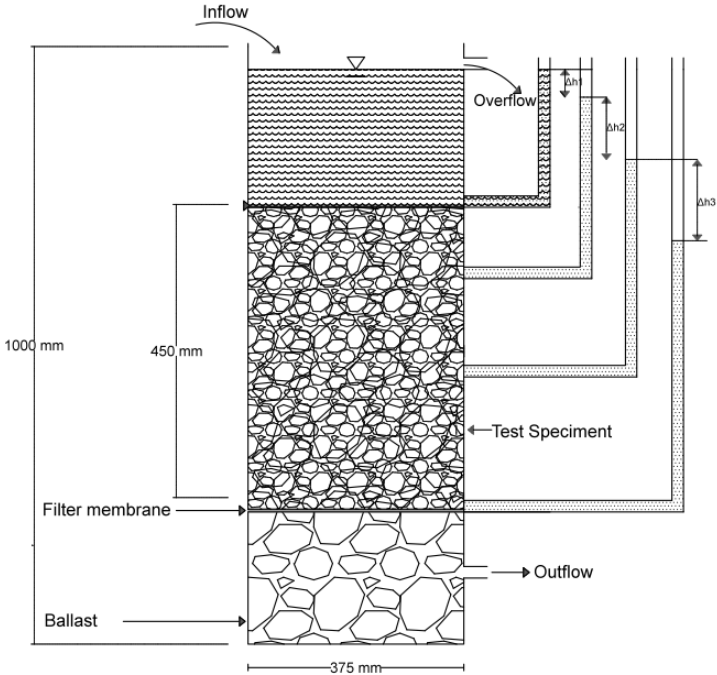


FIGURE 2 Schematic Of Large Scale Permeameter Designed For Type B Aggregate Hydraulic Trials

3.2.2 HYDRAULIC TRIALS

After completing the fouling evaluation a series of large-scale permeability tests were conducted to assess hydraulic performance of the filter material. In the tests clean aggregate had foulant added to simulate the process of ongoing fouling over time and as fouling progressed, changes in flow performance were assessed.

3.2.2.1

3.2.2.1 LARGE SCALE PERMEAMETER

The large-scale permeameter (Figure 2) allows the measurement of hydraulic conductivity values for samples with radius of 375mm and depth of 450mm with varying fouling levels under a relatively low constant head.

Four manometers are installed in the permeameter to enable accurate measurement of head drops between three layers of aggregate. In order to prevent fine particles from washing out of the tank, a geofabric was installed on top of uniformly graded coarse aggregate at the lower end of the permeameter.

3.2.2.2 MATERIALS AND METHODS

Type B filter material has been used in the trials to match the material found in the field study; this was installed in three layers. Two types of foulants (sand and clay based) were used. The grading curves and specific gravity of the aggregate fill and foulants are illustrated in Figure 3.

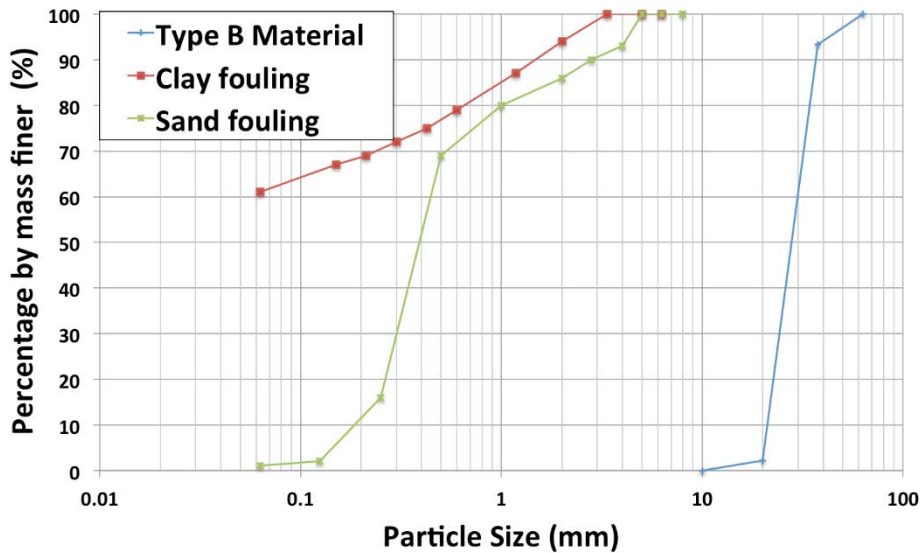


FIGURE 3 PSD Of Fouling Types And Aggregate Fill, $G_{s-Agg} = 2.7 \text{ Mg/M}^3$ $G_{s-Sand} = 2.6 \text{ Mg/M}^3$ $G_{s-Clay} = 2.77 \text{ Mg/M}^3$

To simulate the in service degradation of the trench, fouling material was added at the surface of the tank and allowed to infiltrate within the fill with percolating water flowing into the drain under a low head (maintained by a weir in the apparatus). The effect of different fouling levels, materials and fouling spreading within the tank, was evaluated under fully saturated constant head conditions and assumed laminar flows. Separate permeability measurements were made of the foulant using constant and falling head permeameters.

When steady flow through the permeameter was established, the pressure drop across the four tapings was measured to extract the energy loss between the three layers of material. The mass of water exiting the tank was collected and using Darcy's law permeability values are assessed.

After the test, the sample was excavated and assessed for the position of foulants by grading. The test is repeated twice with the second attempt aiming to represent the effects of surface scarifying on the material. This is achieved by loosening up the surface aggregate and allowing the foulants trapped near the surface to infiltrate deeper in the tank.

Two permeability values are thus assessed for each fouling level, the full sample and lowest by-layer values. The former represents the value between manometers at the top and bottom ends of the permeameter and thus the hydraulic conductivity of the full 450mm fill used in the tank. The lowest by-layer permeability value represents the lowest value recorded at any given layer at the first or second trial (before and after scarifying).

4 ANALYSIS AND RESULTS

4.1 SITE INVESTIGATION SAMPLING AND FOULING INDICES

It was evident from the initial visual assessment of the site-collected material, that fouling levels increase at greater depths within the trench (this generally agrees with published data for Type B aggregate (5-7)). The filter drains assessed have been in service since 2003 and only limited cases of localised water ponding have been reported over the period of operation; this is attributed to the collection of detritus at the surface layers of the trench. As a general remark the filter drains within the network appeared to be functioning at an acceptable level.

The subsequent grading of the material from each layer (typical data are presented in Figure 4 for trial hole C) reveals a location and depth specific variation of fouling levels. For trial hole C, the particle percentage (by mass) passing the 10mm sieve size increases from 27% (surface level) to 60% (800mm deep) whereas in trial hole D and for the same depths, the percentages are measured to increase from 12% to 34%. *Table 1 presents the fouling levels of all samples collected.*

The fouling material composition is also found to vary according to depth; deeper within each trial hole the percentage by mass passing the 0.063mm size sieve increases. Higher fractions of clay and silt are found at layers further down the drain; it is thus expected that the foulant deeper in the trench will have a bigger impact on drainability, as it is found to be 'richer' in fines content.

The hydraulic conductivity value of the detritus/foulant alone collected at the surface of the trench is measured to range between 1.7 and 2.26 mm/sec. Fouling material collected at lower layers is expected to fall at a lower end of this range. The void ratio of the 75mm top-up material is measured to range between 0.82 and 1.017 while the one for Type B material is calculated between 0.60 and 0.68.

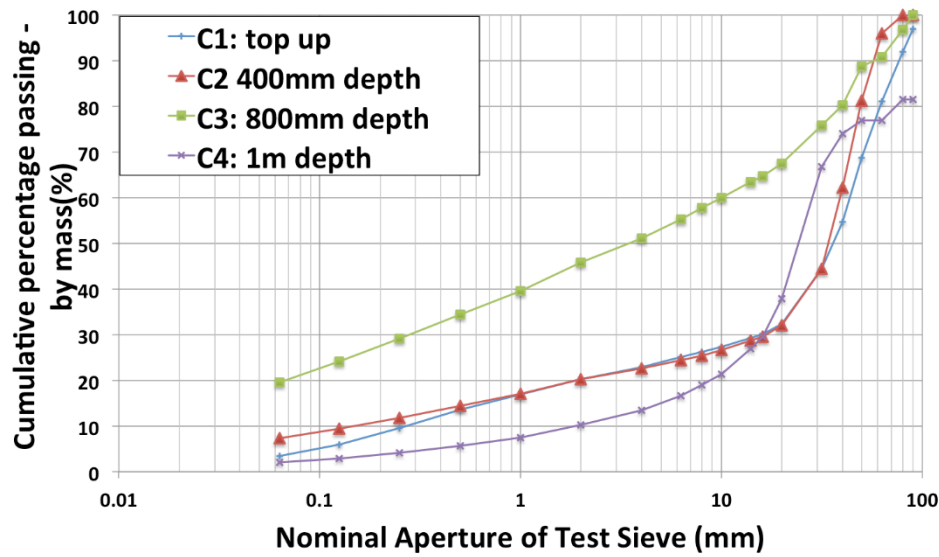


FIGURE 4 Layered PSD Curves For Location C

Adopting the three fouling scales proposed above, Table 1 illustrates how the PSD curves of the 14 samples can be expressed in terms of P_{DF} , R_{F-A} and R_{FV} . Higher values of P_{DF} and R_{F-A} indicate higher concentrations of foulants whereas lower values of R_{FV} suggest a smaller available free void space and thus an anticipated lower hydraulic performance. Taking for example sample C at depth between 600 and 800mm the percentage drain fouling is calculated at 79.5% indicating large concentration of foulants within the sample. As anticipated the foulant to aggregate ratio is also high, 2.24, indicating that the solid volume of fouling material in this particular sample surpasses the solid volume of the Type B aggregate. Lastly as expected the fouling material for the same sample occupies 100% of the available void space giving a free voids ratio of 0. At this point the drainability of the section is expected to be a function of the foulant rather than the aggregate itself.

The bigger particle size adopted at the surface of the trench offers a larger void space and in principle allows detritus to infiltrate into the drain faster, limiting obstructions and the levels of fouling near the surface of the trench. This suggests that the 75mm surface material in this particular design will generally remain free of road detritus; the data presented in Table 1 supports this assumption. For Location C, the P_{DF} at the top 300mm is calculated at 30% the R_{F-A} at 0.47 and the R_{FV} at 0.42. As the Percentage Drain Fouling increases by 4% for the next layer, the Foulant to Aggregate ratio increases by 0.07 and the Free Voids Ratio reduces by 0.30; the reason here being the smaller void space offered by the type B material when compared to the 75mm top up aggregate.

TABLE 1 Fouling Levels And Fouling Characterisation Using P_{DF} , R_{F-A} and R_{FV} for Field Samples

Depth	Location	$P_{10} - P_{0.063}$	P_{DF}	R_{F-A}	R_{FV}
		% - %	%		
Top 300 mm	A	27 - 3	30	0.42	0.48
	B	23 - 3	26	0.37	0.55
	C	27 - 3	30	0.47	0.42
	D	12 - 2	13	0.17	0.79
	E	21 - 4	24	0.34	0.58
300 - 600 mm	C	27 - 8	34	0.54	0.12
	D	16 - 3	19	0.26	0.58
	E	11 - 4	15	0.15	0.76
600 – 800 mm	B	13 - 6	19	0.16	0.73
	C	60 - 20	80	2.24	0
	D	34 - 8	42	0.69	0
	E	29 - 8	37	0.55	0.11
>1m	C	21 - 2	23	0.33	0.47
	D	15 - 5	20	0.25	0.59

Note: $G_{SA} = 2.90Mg/m^3$, $G_{SF}=2.56Mg/m^3$

Also sample >1m are extracted below the geofabric that limits particle ingress thus the observed drop in fouling levels.

4.2 HYDRAULIC TRIALS

The permeability of the laboratory sand foulant was measured in the range of 1.62 to 1.94 mm/sec whereas the one for clay was measured in the range of 1.48 to 3.42 x 10⁻³ mm/sec. The former loosely coincides with the permeability value of the foulants as extracted from an in situ drain (1.7 to 2.26 mm/sec) thus the sand foulant is expected to realistically simulate the in service fouling conditions.

As anticipated, the hydraulic conductivity of the aggregate drops with increasing levels of fouling (see Figure 5). Even though the drop for relatively small levels of fouling (higher values of RFV) is steeper, the overall drainability of the section (full sample value recorded) is still safely above minimum performance requirements established in the network's HFD contractual requirements.

At RFV values below 0.6 the reduction in the layer specific (lowest by layer value extracted in Figure 5) value for increased levels of fouling becomes marginal for both sets of trials (sand and clay based). A convergence between the two values is reached at a lower RFV values (0.46 and 0.49 for sand and clay fouling respectively). This suggests that the fouling material has occupied a significant amount of the previously free voids, and dominates the overall flow performance of the evaluated aggregate fill.

Within a full 450mm sample, highly concentrated fouling in a thin layer affects the performance of the whole material. The minimum by layer permeability value is initially extracted at the top layer for generally fouling-free samples ($R_{fv} > 0.65$). By 'scarifying' the

aggregate during the second run for each fouling level, the overall capacity (full sample value) of the fill would then increase as the previously concentrated foulants spread within the lower sections of the material. As it is, the initially highly fouled state of the surface material largely impedes the free flow of water through the top layers of the aggregate. For RFV values lower than 0.65, pushing the fouling material deeper in the tank further reduces the overall permeability (the full sample value extracted before scarifying is higher than the one extracted after allowing foulants to infiltrate deeper within the aggregate). This suggests that the fouling levels within the lowest two aggregate layers in the tank move towards a critical state and steadily converge to a terminal hydraulic conductivity value, which will be a function of the fouling material. This describes a bottom up fouling pattern. It also suggests that scarifying the top 100-300mm of a trench for sections with Rfv values below 0.65 may lead to reduced performance.

The minimum hydraulic conductivity of sand based fouling trials is converging to a permeability value near 1.9 mm/sec. Increasing the foulants within the tank below Rfv = 0.50 resulted in no significant drop in this. The average performance of the whole fill (full sample permeability value) is at that point approximately twice as large as the minimum value extracted at the lowest layer, suggesting that enough free void space is still available in the top two layers of the permeameter. Since the assessment of the backfill should be based on the full extent of the drain, it can be safely assumed that even with the lower sections of the fill being in a highly fouled state, the sample will still carry enough runoff removal (and storage) capacity if the foulants have infiltrated deeper within the tank leaving the voids space higher up largely free of detritus (to also allow horizontal flow to outfall assuming a bottom up failure pattern). The minimum service performance of 6 mm/sec is reached in the sand fouling based trials near the Rfv = 0.55 (this occurs at a higher Rfv when clay fouling is used). When highly fouled states are approached near a Rfv value of 0.45, the vertical permeability measured is approximately half the initial design value required.

For the clay-based fouling trials, and when the concentration of fines is higher within the fouling matrix, the terminal hydraulic conductivity value of the aggregate will be significantly lower; the lowest recorded value is at 0.5 mm/sec. While the trials aimed to extract the effect of scarifying for each sample, clay infiltrates within the aggregate material swiftly and builds up near the geofabric at the bottom of the tank rather than at the surface. In principle this particular foulant composition fails to capture the extent of in service fouling materials; clay based fouling will have orders of magnitude lower hydraulic conductivity compared to that measured for the in-service fouling conditions. It is though used here to illustrate the importance of evaluating both the levels and composition of the foulants found in a highway filter drains. The nature of the fouling material will affect the value of permeability in the critical range of RFV and evidently clay has a larger impact on hydraulic performance than sand based foulants.

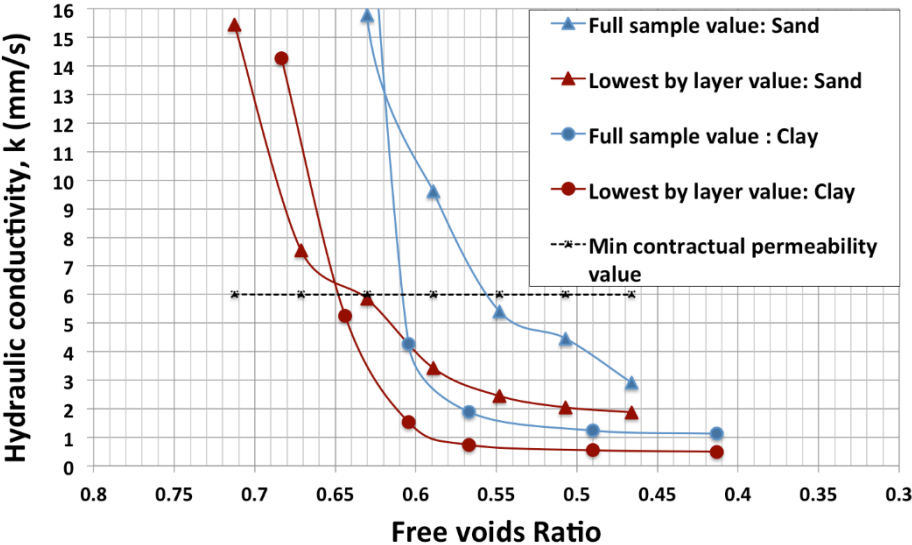


FIGURE 5 Extract of Permeability As A Function Of R_{FV} Using Sand And Clay Fouling Material in Type B Filter Material.

5 DISCUSSION

The hydraulic conductivity and thus the in-service performance of the aggregate fill drops with increasing levels of foulant filling up the aggregate voids. The three fouling scales presented offer an engineered condition assessment methodology requiring different evaluation approaches. Where the Percentage Drain Fouling is the most easily extracted index, it fails to address the variation in void space that arises due to the large gradation envelopes and the two types of aggregate than can be used in design of HFDs (Type A and Type B). This is particularly important in the assessment of the in-service drains also because of the nature of the top-up material used in the network under evaluation (larger particle diameters and thus larger anticipated void space in the top 300mm of the drain trench). The use of PDF could drive unnecessary maintenance requirements higher by underestimating the available free voids volume in the surface layers of the trench. The two volume based indices can potentially tackle this. The Foulant to Aggregate Ratio is based on establishing the volumetric ratio of foulants (particles passing the 10mm size sieve) to the aggregate volume (particles retained at the 10mm size sieve). However, similar to the Percentage Drain fouling it doesn't take directly into account the void space of the evaluated samples. The suggested Free-Voids Ratio, R_{FV} , is calculated by estimating the initial void space in the trench and extracting a representation of the available free voids volume. It is thus expected to denote the fouling levels of the aggregate with higher accuracy in the field. It is also in the intention of the writers to prioritise the use of a volumetric fouling scale with Non Destructive Testing and Evaluation assessments as part of the ongoing research project. R_{FV} is thus the index taken forward in the hydraulic trials and evaluated in context.

The field evaluation and subsequent sampling and sorting suggest a location and depth specific variation of fouling levels and foulant composition in drains. The drains generally

seem to operate at an acceptable level (no significant water ponding during rainy field evaluation or past evaluations) and the fouling index indicates RFV values ranging from 0.79 to 0 while the permeability of the foulant collected at the surface of the trench is similar to a sand based fouling material (1.7 – 2.2 mm/sec). This suggests that a number of highly fouled layers can be found within the field dataset but in most cases the full drains' capacity still surpasses the minimum performance requirements against deterioration predictions of a 10-year operational life; this due to large trench sections with high RFV values and also potentially due to horizontal flow in the trench that is not considered in design and build operations that solely factorize vertical permeability.

The main in-situ fouling pattern identified on site, is that of increasing fouling levels deeper within the trench and a bottom up failure; location B being the exception with higher concentrations of foulants near the surface of the HFD section. If the latter holds true and high levels of foulants are concentrated at the surface of a trench, the initial runoff removal would be largely impeded near the surface, resulting in water ponding on the carriageway. Scarifying is included as a network-wide maintenance requirement as a preventive measure against reduced drainage performance. The hydraulic trials suggest that pushing foulants deeper within the trench will eventually result in reduced hydraulic performance. A point is reached where fouling concentrations surpass a critical level deeper in the drain and a foulant-dominated layer is formed. It is generally accepted (5-7) that scarifying has been used to effectively tackle reduced performance in the field caused by increased levels of fouling near the surface of the trench. The approach may not work in the longer term if proper evaluation of the full trench depth is omitted from any condition assessment.

6 CONCLUSION

The existing design manuals suggest a 10-year HFD asset operational life but fail to employ any significant performance standards, a fact that could lead to unnecessary renewal or maintenance interventions if applied universally within a highway section or unexpected drainage failures. Through 10 years of operation, evaluated filter drains are found to be functioning at an acceptable standard with a limited number of localised failures attributed to highly fouled layers at the surface of the trench.

In the absence of any rational assessment methodology, this paper describes a possible way forward for filter drain fouling characterization by employing a set of basic sampling techniques and hydraulic testing. Mapping a fouling scale with a hydraulic performance enables a rational condition classification, which can be assessed via simple laboratory tests. The permeability of foulant collected from an in-service drain is calculated to range between 1.7 and 2.26 mm/sec suggesting a sand-dominated particle matrix. Based on the hydraulic trials it can be assumed that for highly fouled states the permeability of the trench will converge to the one of the foulant itself.

The requirement to establish a suitable in-service drainage performance boundary is required. It is shown that a holistic and rational evaluation of a filter drain section should employ means other than surface visual indicators that are subjective and potentially misleading. The fouling characterization through a mass or volumetric fouling index can be correlated to an in-situ hydraulic performance and the Free-Voids Ratio is proposed as a means to evaluate fouling concentrations within the filter drain trench.

The permeability testing suggests that the extent, spreading and type of fouling is of paramount importance in determining how the filter aggregate performs. It is also suggested

that existing maintenance approaches could be problematic as they lack rational justification. This goes on to suggest that i) a layer by layer analysis of the filter trench is required and ii) scarifying the surface of the trench will be less effective and possibly problematic if the concentrations of fouling material in the trench are above a specific level.

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APPENDIX B HIGHWAY FILTER DRAINS: PRECURSORS FOR MAINTENANCE MANAGEMENT (PAPER 2)

Full Reference

Stylianides, T., Frost, M.W., Fleming, P.R., El-Jaber, A., Mageean, M., Huetson, A. and Klimczak, T., 2015. Highway filter drains: precursors for maintenance management. *Infrastructure Asset Management*, 2(4), pp.159-172

Abstract

This paper conceptualises and presents a number of asset management building blocks required to establish holistic management for highway filter drains in the UK roads network. This is accomplished by evaluating current maintenance and management thinking and by identifying how existing strategies are lacking and potentially unsustainable. A condition assessment regime is hence described, tied to a measure of filter drain level of service (drainability) and an asset-specific ageing/renewal model that adopts six discreet condition bands is proposed. For this model to hold true, the Markov process is assumed to represent cumulative damage in a network. Drawing from relevant asset management concepts, a decision support tool to inform and optimise managerial decisions in respect to maintenance planning and resources allocation is also described

Keywords – Maintenance & inspection management; roads & highways

Paper type – Journal Publication

1 INTRODUCTION

Highway filter drains (HFDs) are aggregate-filled trenches fitted with a porous carrier pipe at the base used in the UK to drain significant lengths of the highway network. The granular material used, which is typically (but not restrictively) exposed at the surface of the trench, allows for efficient removal of pavement runoff due to its high porosity. It also enables the removal of subsurface water from the pavement foundation and structural layers. HFDs thus act as a combined drainage system. Such systems can be advantageously employed in cutting situations requiring significant groundwater removal, and because of their large hydraulic capacities, they can also safely remove surface water during heavy storms. Filter drains are constructed in verges and/or central reserves adjacent to the low edges of pavements enabling surface water to run off the pavement directly onto the trench and then permeate through the aggregate backfill to the pipe at the base of the drain (Highways Agency, 1998).

HFDs have a finite operational life because of the reduction of free voids space of the filter material as road detritus and other fines enter the drainage trench, restricting the free flow of water. Currently, there are no formal systems in place to manage or monitor the performance of the drains and maintenance is typically carried out as reactive work (find and fix) or emergency work. Planned maintenance that is undertaken normally tends to be based on empirical evidence or experience in a given network with little formal monitoring or long-term planning of investments.

The paradigm of management of highway assets has moved over the years towards proactive philosophies, sustainable thinking and rational economic justification of all maintenance and rehabilitation work; this is evident in the various publications addressing the need for efficient highway asset management (AM) presented in recent years (DFT, 2014; BSI, 2014; Taggart et al., 2014; UK Roads Board, 2005; UKRLG, 2013). These documents typically offer a high-level overview of the fundamental concepts to be developed and adopted by local authorities and network operators to meet the minimum requirements of AM systems. They thus usually introduce strategic frameworks to address what should be done with existing groups of highway assets. Although being mainly pavement focused or strategy oriented, they lack the context that allows managers and road operators to establish how these frameworks could be put in practice for drainage systems and particularly HFDs.

This paper aims to establish precursors for a systematised evaluation and comprehensive management of HFDs. Existing HFD degradation characteristics and maintenance strategies are thus evaluated, and concepts of maintenance and asset management (MM, AM), condition assessment and deterioration modelling are summarised and mapped to the drainage system in question. To support the development of a maintenance and management platform for this particular type of drainage asset, a set of management building blocks and a number of HFD ad hoc variables to be embedded within such a platform are hence defined and proposed.

The organisation of the paper is as follows: The next section presents existing maintenance thinking and defines by evaluating HFD maintenance practices the need for a better management approach. In the third section, AM concepts are briefly introduced in an effort to identify those elements that are required to form a suitable filter drain management platform. This enables the writers to conceptualise in the fourth section a condition assessment regime mapped to an anticipated level of performance. Finally, a deterioration modelling approach to be embedded within a decision support tool (DST) is described in the final section.

2 HFD DETERIORATION AND MAINTENANCE THINKING; THE NEED FOR A BETTER APPROACH

There is nothing novel about introducing AM thinking to HFD; the principles adopted (on a strategic level at the least) all over the highway sector for individual asset categories in the last four decades could in principle be applied to HFD management. With vast lengths of filter drains installed in the UK highways network, there will soon be a backlog of maintenance work and a requirement to invest in an intelligent and rational HFD-specific management system (MS). If the climatic changes and their effect on drainage assets are also taken into account (such systems will eventually be further stressed and there will be a requirement for increased runoff removal efficiency), it can be proposed that the development of a structured methodology to support maintenance decision making should be prioritised sooner rather than later.

To move focus from an approach that solely factorises short-term rehabilitation needs to a methodology that satisfies both the short-term integrity and long-term sustainability of HFD, the current HFD service and deterioration understanding and the existing maintenance and rehabilitation frameworks are evaluated here. How the current (maintenance) thinking translates to a need for a better management approach is thus identified before a more structured representation of the missing HFD AM elements can be proposed through this work.

2.1.1 CURRENT HFD DETERIORATION UNDERSTANDING

Current UK design guides suggest that HFDs should achieve an operational life of approximately 10 years. The filter material is then expected to require replacement or recycling, and this is often included in maintenance plans. However, during filter drain field evaluations (Farrar, 1994; Farrar and Samuel, 1989; Samuel and Farrar, 1988), acceptable performance of drains have been observed after 20 years of operation with minimal or no maintenance undertaken. These reports have also shown that there can be a differentiation between the service life of type A and type B (types A and B define different gradings of filter material with type A being finer) backfilled trenches and an implied correlation between filter specifications and modes of failure. Type A is reported to be prone to collecting road detritus at or near the surface of the drainage trench. Some of the key findings of these studies indicate poor construction standards and use of material that does not meet specification criteria, hence implying that the asset's longevity may have been affected by poor construction quality. To fully capture a more accurate representation of HFD (average) service lives (and taking into account the aforementioned work), there is a need to further evaluate deteriorated drains and collect appropriate condition data.

Since these reports have been published, there has not been any other significant output (academic or industrial) whatsoever regarding the asset's performance and/or its degradation characteristics and, more importantly, how to address key maintenance planning issues.

One exception to this, Rowlands and Ellis's (2007) work, addresses in situ recycling as a means of introducing a level of sustainability and control over HFD maintenance operations. The authors focus on a novel rehabilitation approach and offer an overview of waste management issues during maintenance work but do not introduce a theoretical framework to

support intervention time frames and holistic management; they instead adopt the existing empirical HFD service life projections often employed in the sector.

In the meantime, Highways England (HE) has brought forward a policy of non-recommendation for use of HFD in new projects, and this drainage option remains in UK standards for maintenance and rehabilitation operations. There are a number of reasons for this that may be attributed to design limitations (stone scattering as a safety hazard, cost of suitably graded stone in some regions), lack of engineered assessment methodologies to evaluate performance drop (malfunction of drainage system may go unnoticed) and the requirement for regular maintenance and replacement of filter stone at end of service life. These should presumably reinforce the case of introducing a holistic MS to deal with HFD in the roads network.

2.2 DEFINING MAINTENANCE AND MAINTENANCE STRATEGIES

In terms of maintenance thinking, routine, corrective, preventive, predictive, proactive, and reactive strategies are terms often adopted in the industry to deal with the various approaches used for management of the physical assets in the UK's highways. These are often interrelated; the most obvious distinction between the strategies is based on whether failure has occurred even though the definition of a failed state for a number of assets remains in many instances blurred (Uddin et al., 2013). It is thus easier (in terms of HFD management) to define maintenance using the terms proactive (prevent impending loss of acceptable drainage capacity and employ evaluation methods factorising condition or time) and reactive (run asset to failure and treat once drainage capacity is below acceptable thresholds, or a firefighting approach to maintenance (Swanson, 2001)). This of course requires a clear definition of the asset's functions, how these are impaired, what the relevant failure modes are, what causes them and how these can be detected, and lastly what the impact on the pavement system and road user will be.

For HFD maintenance, interventions are still largely regarded as necessary repair work. While the importance of drainage has been highlighted as a main factor affecting long-term pavement performance (Cedergren, 1974; Hudson, 1968; Mallic and El-Korchi, 2013; Robinson et al., 1998) and driver safety (Johnson and Chang, 1984), there has not been a targeted effort to introduce the means for holistic drainage management or decision-aid toolkits. Drainage is not central in pavement management systems (PMSs), and engineered assessment techniques and rational maintenance strategies are in many cases omitted or considered to a lesser extent (Haas et al., 1994; Robinson et al., 1998). HFD are often in service until they fail in removing surface runoff from the pavement in an efficient manner, and there is still no way to predict or even classify functional failures. The alternative maintenance thinking (the first being in essence reactive) suggests implementing a time-based approach. Under this strategy, HFD maintenance and rehabilitation may be specified in a cyclic fashion (annual or biannual maintenance cycles or hard-time replacement at the end of the HFD design life) – see Figure 1

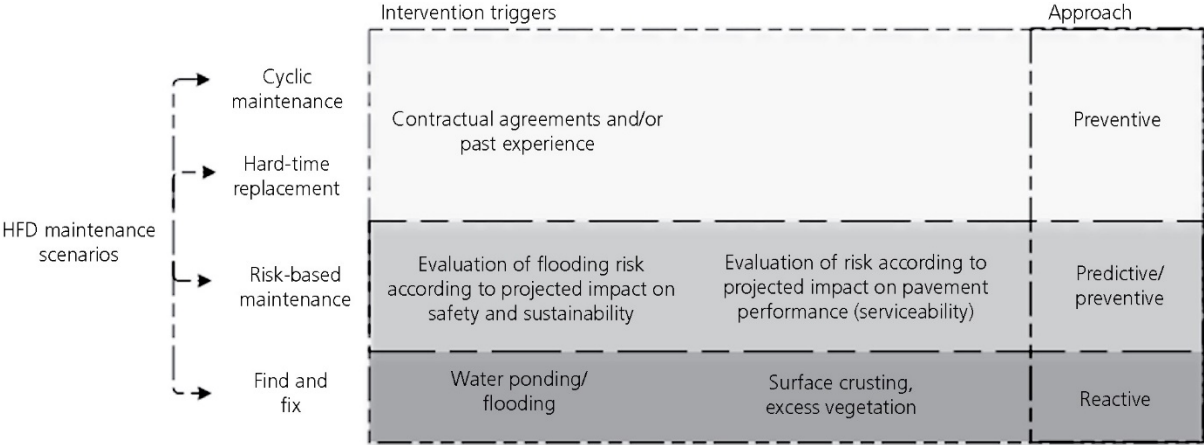


Fig 1 Current maintenance thinking, intervention triggers and philosophies

Time-based maintenance (TBM) policies are usually derived on the premise of a bathtub curve (Klutke et al., 2003), which maps the gradual deterioration of the asset to increasing failure rates as cause and effect after a given service period (Ahmad and Kamaruddin, 2012; Yam et al., 2001). Under this scenario, maintenance, renewal and rehabilitation (M,R&R) tasks are scheduled at predetermined time or service intervals, and in general terms, time between successive interventions remains constant for asset categories with similar design characteristics. If these assets do not present a narrow failure distribution pattern that can be accurately predicted (Swanson, 2001), two scenarios will subsequently be presented: one, only part of the useful life of the asset will be utilised between interventions, or two, failures will not be addressed in a timely manner. Both scenarios will eventually incur additional costs to road operators and users by imposing unnecessary treatments or unexpected failures, with the latter imposing additionally a critical safety hazard. Safety implications (in terms of limiting water accumulation on the pavement surface and all relevant hazards) thus commonly dominate the planning process of maintenance operations under a reactive philosophy.

This suggests the reassessment of the existing HFD management thinking in order to establish how effectively maintenance interventions are planned and undertaken. From the studies and field evaluations reported above, it can be concluded that the degradation characteristics of in service HFD will not (restrictively) be a function of operational life (or the current definition of HFD service life is misleading). Takata et al. (2004) suggest that rates of deterioration for various asset types depend on operational and environmental conditions, and clearly, for filter drains, construction quality and maintenance history will also have a role to play. Initial projections of design lives of 10 years seem to be an underestimate, but functional failures that are related to the surface water removal capacity can appear within this period and will require attention. Under a TBM approach, M,R&R actions that are usually trench scarifying or vegetation control can be specified on annual/biannual cycles; aggregate replacement (HFD reconstruction) is due after 5 or 10 years of service life.

2.3 A BRIEF OVERVIEW OF HIGHWAY INFRASTRUCTURE ASSET MANAGEMENT (IAMS) AND A NUMBER OF DRAINAGE MANAGEMENT FUNDAMENTALS

Having established an overview of the current HFD maintenance thinking, the need to redefine the existing HFD-specific management model is proposed; an overview of a number of IAMS fundamentals is thus presented as the topic of AM is evaluated adopting top-down (British Standards, good-practise guides, design manuals) and bottom-up (drainage condition assessment literature) approaches. Some key features of PMSs are described, founded upon generic AM thinking, and a number of elements that can be transferred to a filter drain management framework are thus identified. This section examines how the combination of existing AM know-how and tactical drainage-explicit assessment literature may lack some of the key fundamental prerequisites required to move towards holistic management of this particular type of drainage asset

2.3.1 THE BUILDING BLOCKS OF AM – A TOP-DOWN APPROACH

A generic framework that describes the requirements for holistic AM is proposed by Hassanain et al. (2003) using five key operations, which are

- identify assets,
- identify performance requirements,
- assess performance,
- plan maintenance,
- manage maintenance operations.

Similarly defined AM frameworks can be found in the literature; in Wittwer et al. (2002), condition assessment and trade-off analysis are included in the basic cycle of an AM framework (physical condition and asset performance as descriptors of the effectiveness of service delivery are often used hand in hand), whereas Dornan (2002) goes into further detail in asset renewal/replacement analysis methods (life-cycle cost, cost-effectiveness analysis or equivalent annual cost) and asset disposal policies. In practice, even though different definitions can be found, an AMS is the combination of engineering and business practices to support decision making at the strategic, network and project levels; in other words, it is a way of doing business by adopting the right procedures to achieve results cost effectively with the limitation of sparse resources (Cambridge Systematics et al., 2006; Godau, 1999).

Individual asset-specific MSs like PMSs were founded on this theoretical framework focusing on the key objective of cost-effective infrastructure maintenance and operation. PMSs are essentially the collection of all tools, technologies and processes that help managers make better decisions and manage their pavements more effectively. Their implementation since the late 1960s (Markow, 1995) came as a response to the shift from design-and-build operations

to the repair-and-maintain mode. At this point, PMSs are abundantly available for use but other highway-related MSs have emerged to deal with bridges (bridge management systems), safety (safety management systems) and in-house maintenance operations (maintenance management systems) (Li and Sinha, 2004).

While all these systems address different asset categories and functions within the highway network, they integrate at their cores the same systems thinking and management principles (this work emphasises how drainage management has not yet embedded such an approach). They are fundamentally information driven, heavily dependent on databases (inventory, condition, historic maintenance, budgets, M,R&R options/impacts/costs) and employ a particular type of analysis that allows asset managers to fine-tune interventions, optimise asset life cycles and carry out investment decisions for preservation, expansion and operation of any given network. The data required for a MS are produced by monitoring and inventory activities, while modelling provides the tools for planning, trade-off analysis, ranking, and optimisation (Li et al., 1997). For PMS, pavement performance models adopt either deterministic (Abaza, 2004; Abaza et al., 2001; Wong et al., 2003) or probabilistic (Abaza et al., 2004; Golabi et al., 1982; Li et al., 1997) approaches, and DSTs that integrate prioritisation or optimisation models.

The recently published Highways Infrastructure Asset Management Guide (UKRLG, 2013) complements the ISO 55000 (BSI, 2014) series on the topic of AM in the UK. The latter supersedes the previous AM standards (PAS, 2008) and now offers an overview of AM, the requirements for an AM system and the guidelines for the application of ISO 55001. The ISO is a high-level strategic guide that introduces systems thinking and AM organisational precursors in a business-oriented manifesto that aims to standardise AM. A tactically oriented document, the UKRLG (2013) guide focuses on physical assets in highway networks, offering 14 recommendations to achieve an appropriate level of benefit from AM. These recommendations deal with various themes, including life cycle plans, performance management and monitoring, risk management and AM policy and strategy. The drainage-specific guidance document HMEP (2012) in turn focuses on establishing a cost-effective approach to managing drainage assets, based on building drainage-specific databases (inventory, condition, maintenance intervals, frequency of failures, maintenance requirements, etc.) and using this information to apply relevant AM principles. The guide highlights various strategic requirements to be developed and offers a number of concise recommendations (i.e. the requirement to address the causes of problems as opposed to symptoms and the requirement to use asset data to focus, support and inform maintenance activities mapped to overall AM objectives). It also proposes the adoption of proactive and prioritised programmes and the need to support these using asset condition data.

All these documents describe a 'high-level' framework to be developed but do not go into detail with regard to the inventory data to be collected, the condition metrics to be established, the performance indicators to be introduced or, lastly, the deterioration and maintenance optimisation models to be built. For a number of asset types (i.e. pavements) a wide spectrum of these parameters can be found in relevant AM or asset assessment literature. This will not hold true when drainage systems are to be evaluated; this simply highlights that a top-down approach through the available strategic and tactical publications will enable road administrators, operators and local councils to establish the required AM framework (or the AM know-how) but eventually the practical end of such a system will need to be addressed: what kind of data are to be collected, how are these to be used and in what sense will the outputs reinforce the case of AM and be of true value.

2.3.2 MANAGING DRAINAGE ASSETS: THE BOTTOM-UP OPTION

At the lowest AM tier, with a more operational focused document, Spink et al. (2014) approach the issue of managing drainage assets in the latest CIRIA publication that addresses some of the questions raised in the previous sections. The guide thus includes elements for inventory and condition data collection and evaluation and a proposed performance assessment regime. Being primarily focused on condition appraisal, the publication defines structural and service conditions as the two main parameters to be extracted through drainage condition surveys building upon visual evaluation. Five discrete condition bands in a one-fits-all assessment approach are included in the text.

While the proposed bands could be used to characterise individual HFD sections, the methodology embedded in the assessment procedure to reach them is rather generic. The deterioration characteristics of HFD are not considered, and the boundaries proposed to establish the discrete condition states are largely empirical; these are derived by rating the asset employing visual means rather than identifying and measuring the type and extent of the severity of fouling in an evaluated section. In fact, no framework for intrusive (or other non-destructive) evaluation is described in detail and thus a large portion of the information required to assess HFD is omitted (severity of sedimentation and extent within filter media tied to HFD failure modes). The condition evaluation adopting this approach would retrospectively address only one of the (two) HFD failure modes; that would be the reduction of surface runoff removal capacity (functional failure) due to surface crusting (failure mode), and thus, the duality of this particular drainage system is ignored.

Performance assessment in the guide is similarly based on visual surveys, but these can take place only when water can be found within the system (making assessments impossible during dry periods) or the combination of the two condition components identified (structural and service condition as a proxy for performance). The former approach is largely reactive as it suggests addressing the symptoms of HFD deterioration (reduced performance) as opposed to what causes this (sedimentation and reduced void space in trench) but can potentially allow the identification of flooding hotspots and be of value at the network level. The latter is again based only on evaluating the exposed filter media and thus is bound to provide limited information on the overall drainability of a section.

In simple terms, the major issue with this assessment approach is that the essence of fouling, its extent within the HFD trench and how that correlates to the drainability of a section are not explicitly or adequately considered in determining maintenance and renovation strategies. Since the sedimentation levels are not quantified, the actual capacity of the drain to remove water from the pavement system is not considered. In truth, a visual inspection-based condition-rating index can offer a quick evaluation methodology at the network level, it is though based on rating (rather than measuring) physical characteristics of the aggregate fill and bound to ignore some of the relevant information required to draw conclusive remarks for the current condition of the asset.

Also of interest is how local authorities currently approach the matter of managing drainage assets; adopting the UKRLG (2013) code of practice, condition standards are proposed at three domains here: safety, serviceability and sustainability. Maintenance plans produced by councils, which can be considered the tactical and/or operational side of the AM systems in place, suggest managing drainage assets adopting a risk or a fire-fighting approach

(Bournemouth Borough Council, 2008; Middlesbrough Council, 2006; Suffolk County Council, 2008; Walsall Council, 2012).

Such plans will generally include guidelines for managing all relevant transportation assets; in the cases of carriageways, footways or cycle routes (and drawing from the Well Maintained Highways code of practice), a number of condition parameters (deflection, surface defects, skidding resistance, weed growth, slipperiness etc.) are to be measured and mapped against the core objectives of a highway maintenance regime for each domain. Drainage condition standards lack any such parameters or metrics. Instead, the three core objectives are streamlined against flooding risk, which is in principle a measure of performance rather than physical condition. This can be a facilitator of a reactive maintenance philosophy or of a preventive one that is primarily based on subjective indicators due to the lack of other condition metrics.

It is evident that our current thinking is lacking; in terms of planning, management of investments and understanding the factors that drive the deterioration of HFD, our strategies are largely underdeveloped and are primarily based on empirical methods (and thus tend to be reactive). This is due to a combination of factors; drainage has been neglected in the past, efforts to implement assessment techniques only partially addressed AM requirements, strategic guides offer fundamental (strategic) concepts lacking the ‘engineering-end’ of the management equation and empirical and/or time-based approaches offer limited opportunities to evaluate the physical condition of an asset and thus to collect relevant and specific HFD data.

3 (RE)PAVING THE WAY FOR A HFD MM SYSTEM

3.1 WHERE TOP DOWN MEETS BOTTOM UP

Maintenance thinking has evolved in recent decades to meet the requirements for greater dependence on business and engineering principles, use of benefits and costs through what-if and life-cycle scenarios, rationalisation (and thus lesser dependence on generic standards) and, lastly, accountability of data and of performance projections. The sector’s thinking has long moved from considering maintenance as necessary repair work, and the definition of Robinson et al. (1998) of ‘maintenance as a management issue concerned with delivering a defined quality of service, activities and procedures, timing of interventions and resources of people and materials’ conclusively illustrates the fact.

The adoption of AM principles in the highways sector has been briefly described in the previous section. By identifying the gap between introducing the AM know-how and embedding the engineering prerequisites for this to be of value, the development of a set of HFD management building blocks is proposed. Looking to formulate an HFD-specific AM subsystem, the particular characteristics of the asset are to be considered and evaluated in a framework that will be in line with other existing asset-specific AM systems and thus should include

- a geo (or network)-referenced inventory database of HFD,
- condition data classifying deficiencies accountable for drainability levels,

- maintenance history,
- network-level HFD condition distributions,
- ageing/deterioration modelling and estimation of remaining service life,
- intervention analysis and network level program costs mapped to projected condition,
- optimisation of investments,
- project level analysis and tactical overview of maintenance requirements for candidate projects.

The eight elements described here address the five key operations defined by Hassanain et al. (2003), and will in principle allow asset managers to approach the task of managing HFD employing a rational set of decision-aid tools. Some of these themes look trivial and a fair amount of relevant information can be found scattered in the existing literature (e.g. drainage inventory and/or condition data collection in Spink et al., 2014) potentially offering some indications in respect to how to advance the framework. Focusing on HFD-specific elements that deal with quantifying the severity and extent of what drives the drop in serviceability levels and reflect the engineering orientation of the system, a suitable platform that deals with the ad hoc asset design features, how these change during service life and what impact this has on drainage capacity, needs to be defined.

Further expanding the proposed HFD management framework, the need to develop and introduce the methodology to support such elements as condition assessment, deterioration modelling, DSTs and optimisation of investments are identified. The following sections present the case of rational condition measuring that is considered the cornerstone of the aforementioned elements, and the tools that could eventually be developed using engineering assessment techniques.

3.2 MAKING THE CASE FOR RATIONAL CONDITION EVALUATION

3.2.1 ASSESSING PHYSICAL CONDITION: MEASURING RATHER THAN RATING

Condition metrics have been used in various infrastructure asset groups; Sussman et al. (2001) suggest, for example, that in the case of railway condition evaluation, such an approach demonstrates potential for simplifying data interpretation, a fact that should in principle reinforce the case for rational condition measuring.

In pavement surveys, condition metrics quantify (severity) known characteristics of the various issues (distress) and map them to an anticipated level of service. This idea is well communicated and fairly understood. When reduced down to basics, condition indicators for any asset type evaluate how much of a particular type of severity is too much and how boundaries between satisfactory and non-satisfactory performances can be drawn.

3.3 COUPLING HFD AND BALLAST CONDITION EVALUATION

The same principle can be considered when HFD are evaluated. To appreciate how the asset fails and what variables could potentially be introduced in a condition assessment system (CAS), HFD design requirements are initially presented. The aggregate fill used in HFD trenches is primarily based on the type A and type B aggregate envelopes that are expected to offer a range of in situ vertical permeability values. It is practically impossible and, in general terms, infeasible to directly measure how these values change within the effective operational life of an HFD section (or prior to construction). The parameter that can be studied while evaluating anticipated drainage capacity (surface or subsurface) and thus the level of service is the change in available void space within the filter as it reduces for in-service drains with fines infiltrating the trench.

A solution to the problem of classifying drainage capacity of large particle size aggregate materials with similar degradation properties has been developed in the railway industry. The methodologies established here aimed to form an inferred relationship between a fouling index (a quantification of undesirable material within a ballast section) and a drainability level (a quantitative estimation of a section's drainage capacity) for ballast evaluation. Selig and Waters (1994) introduced a simple assessment regime and based their condition evaluation on sampling, sieving and sorting of ballast material, suggesting the introduction of the fouling index. Building upon his work, a number of similar indices have been developed, some taking into account a mass-based quantification of foulants (Sussman et al., 2012), while others a volumetric representation of the fouling extent (Anbazhagan et al., 2012; Feldman and Nissen, 2002; Tenakoon et al., 2012). What is important to extract from these ballast-related condition assessment studies is the proposition that a combination of intrusive and non-intrusive condition assessment surveys that build upon the use of rational condition metrics (often correlating ground penetrating radar surveys with fouling levels (Al-Qadi et al., 2008; Anbazhagan et al., 2011; Leng and Al-Qadi, 2009)) can offer the data required for maintenance planning and efficient resource allocation.

3.4 EVALUATING ASSET DISTRESS AND INTRODUCING CONDITION METRICS FOR HFD

By evaluating the degraded characteristics of in-service drains, Stylianides et al. (2015) proposed the adoption of the fouling scales concept for the quantification of introduced material within an HFD trench. The condition metrics developed (see Equations 1a, 1b, 1c) and coupled to permeability trials suggest that an inferred relation between available void space and hydraulic performance can be extracted from site evaluations. This can in principle enable asset owners to quantify the extent and severity of the deflection and thus to classify in-service performance of individual HFD sections.

$$P_{DF} = P_{\%10mm} + P_{\%0.063mm}$$

$$R_{f-A} = \frac{V_f}{V_a} = \frac{M_f}{M_a} \times \frac{G_{SA}}{G_{Sf}}$$

$$R_{FV} = \frac{V_{VFRA} - V_f}{V_{VFRA}} = \frac{e_{fr} \frac{M_A}{G_A} - \frac{M_F}{G_f}}{e_{fr} \frac{M_A}{G_A}}$$

The fouling indices proposed in the work (fouling here is defined as the material found within a trench which is comprised by the particle size matrix below a 10-mm-size cut-off), are based on both mass and volumetric approaches and have been used to classify field samples collected from drains that have been in service for 10 years at the time. Figure 2 visualises depth-specific condition classification of two particular in-service HFD sections (namely, C and D) using particle size distribution (PSD) curves and two volumetric fouling scales.

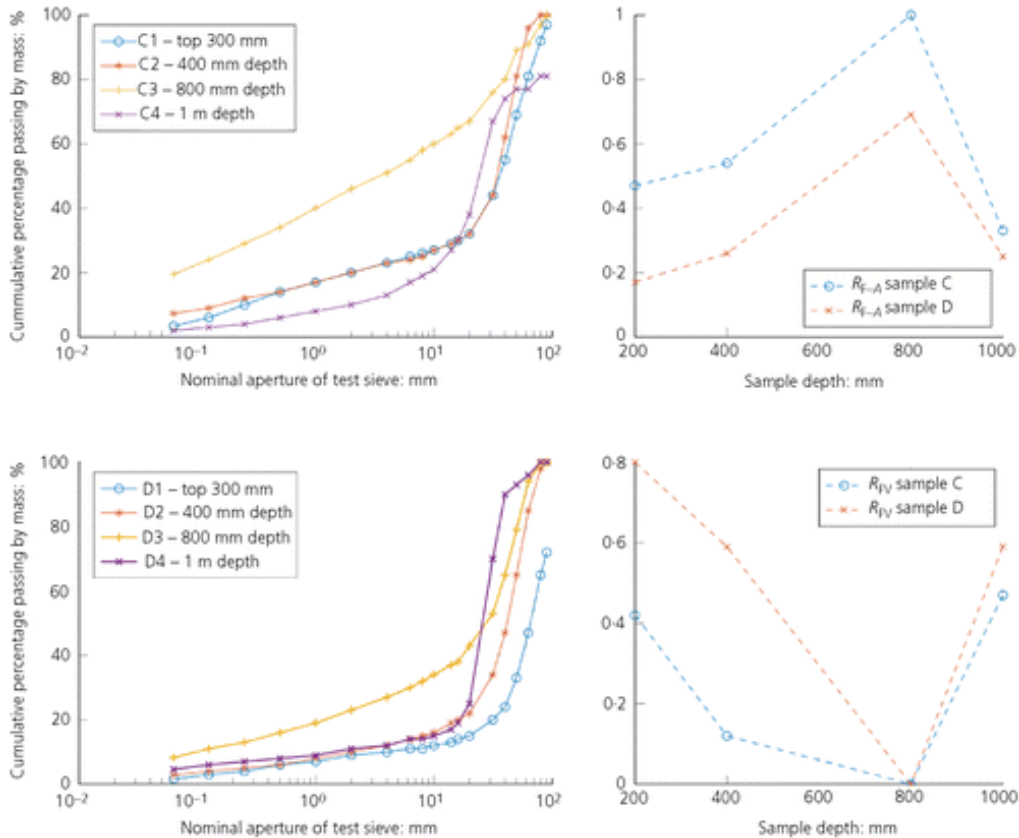


Fig 2 Fouling evaluation of field samples using PSD curves and fouling scales

These indices, used to simulate the drop in vertical permeability values in laboratory tests conducted with type B aggregate material, present how the drop in levels of service of HFD could be estimated as a function of fouling levels (k_v as a measure of drainability; see Figure 3). It has been proposed that for R_{FV} values below 0.6, measured k_v will be a function of the fouling material (foulant-dominated sample), and hence the aggregate fill would rate poorly in terms of drainage capacity.

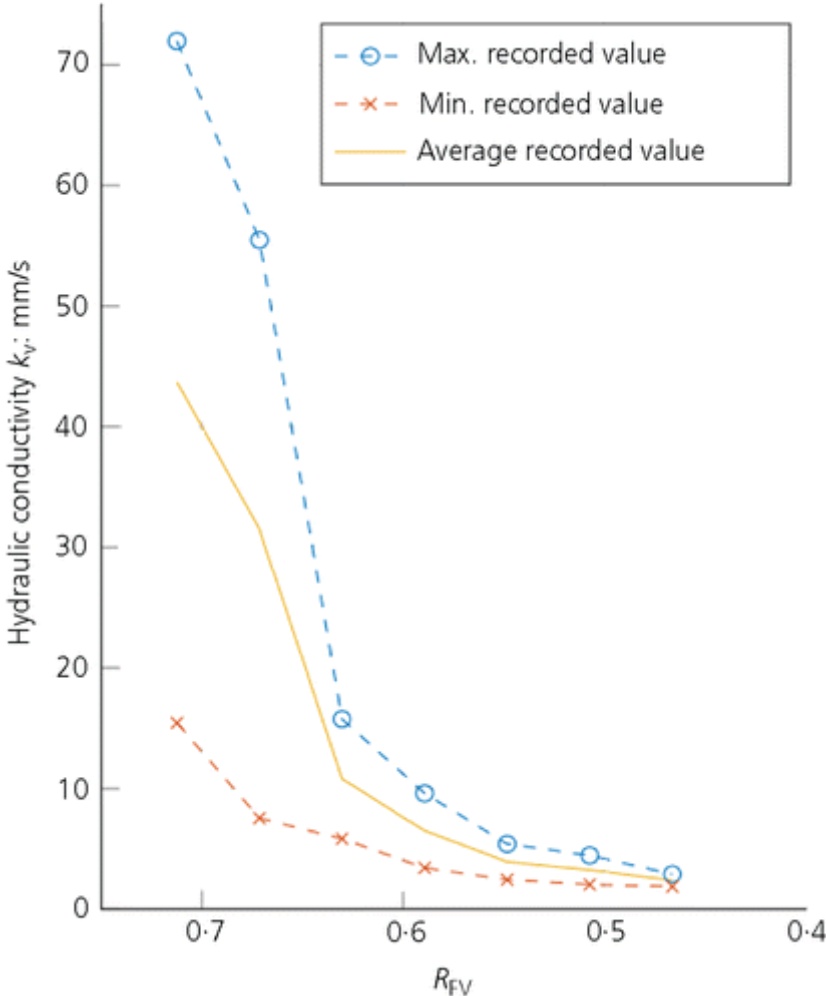


Fig 3 Hydraulic conductivity values as a function of free-voids ratio for reconstructed samples

3.5 AGEING AND DETERIORATION CHARACTERISTICS, FAILURE MODES AND FUNCTIONAL FAILURES

By employing a physical condition classification regime, an engineered assessment system is introduced to quantify the extent and severity of fouling within an HFD section. The next step in formulating the HFD management framework is to use this particular assessment approach in formulating a better understanding of HFD degradation characteristics and a methodology to establish discreet condition bands for the drains. HFD failure modes are thus further evaluated in order to identify and introduce these bands (considering that available assessment criteria (Spink et al., 2014) underplay the duality of this particular drainage design) and to investigate how deterioration can be quantified and modelled.

3.5.1 LOSS OF DRAINAGE PERFORMANCE AND FAILURE MODES

The research published on the evaluation of filter drains in the UK's highway network (see 'HFD deterioration and maintenance thinking: the need for a better approach' section) suggests two distinctive HFD failure modes. While limited, this literature (along with HFD empirical understanding and field evaluation conducted for this work) enables the writers to define HFD condition bands after depicting what each failure mode and functional failure represent.

The first mode, often correlated to the safety aspect, is presented with a near-surface degradation pattern. Sediments block the uppermost of the trench forming a cohesive crust that presents relatively low permeability values (failure cause). This will restrict the free flow of water through the surface of the HFD (loss of function/functional failure) and inevitably runoff will be redirected back to the carriageway, thus imposing a safety hazard for drivers. This moves the HFD condition in an undesirable state that requires timely consideration; the main body of the filter material may at this point remain in an acceptable state. Such failures have been reported to occur every 5–7 years (probability of occurrence), but more quantitative data are required to reinforce this projection. The second failure mode manifests with a bottom-up degradation pattern. Sediments will reach the lower sections of the trench and start building up at the lower end of the HFD, reducing the overall drainage capacity of the filter material. While the first pattern can be currently evaluated by visual means (subjectively at the least), the second manifests well below the surface of the trench and depth-specific assessment (based on intrusive or non-intrusive techniques) is required to assess the expected drop in serviceability levels. Depending on the severity of fouling and extent in the HFD trench, this mode may lead to reduced subsurface and surface water removal capacity. The two modes can be linked in an HFD-explicit ageing model, and this concept is further developed in the following section.

3.5.2 DISCRETE CONDITION STATES: DEFINING THE BOUNDARIES AND EMBEDDING MAINTENANCE ACTIVITIES

With no available quantitative data to represent the deterioration progress of HFD in the highways network, Figure 4 represents a conceptualised definition of six discrete HFD condition bands along with the currently available renewal strategies that restore the condition of the drains from a downstream band (lower drainage capacity), to an upstream condition (higher drainage capacity). The four main states proposed here are excellent condition, fair condition, poor condition and very poor condition with two subcategories representing the top-down failure modes: fair crusted and poor crusted (EC, FC, PC, VPC, FCC and PCC, respectively).

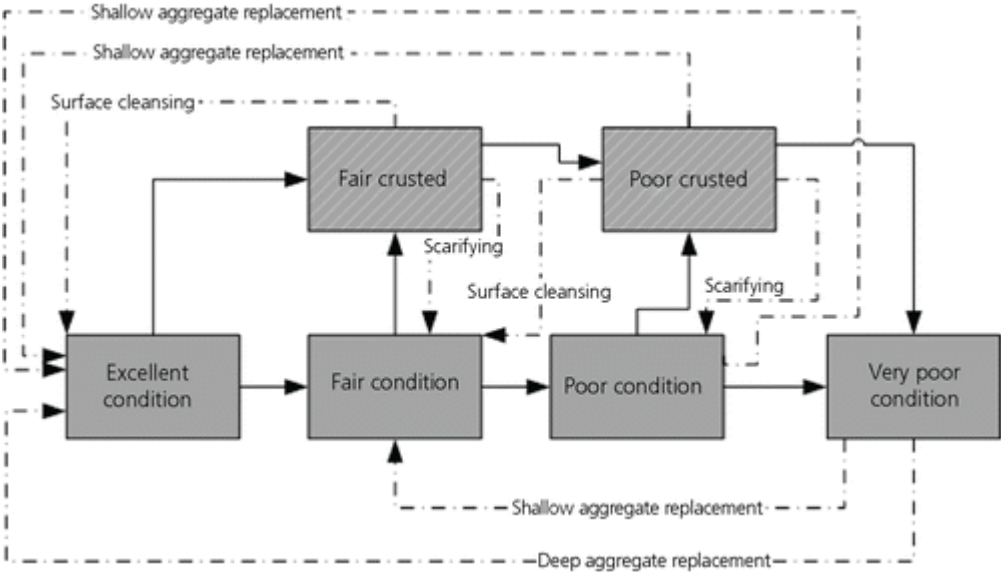


Fig 4 General ageing/renewal model proposed for evaluation of HFD

The two crusted condition bands are critical for safety reasons and are introduced here to enable separation of the two identified failure modes through network surveys and previous field studies. Lastly, the very poor condition represents an HFD section that has surpassed its projected service life (reduced surface and subsurface drainage capacities) and which presents a foulant-dominated aggregate fill. The effect of the various available maintenance options on the overall condition of a section is also visualised in the diagram.

It is crucial to identify and establish for such a concept relevant criteria to form the boundaries between each condition state (linked to the condition assessment regime proposed). The field and laboratory data presented in Stylianides et al. (2015) suggest that a layer-by-layer analysis is required to classify the serviceability levels of the trench and to evaluate the different failure modes. The FC and PC states, for example, are manifested in the uppermost of the drain and can thus be easily identified under a reactive regime; if a more proactive (or on-condition) approach is required (and this paper suggests that this is in fact the case), a quantification of fouling levels (FL) mapped to anticipated drainage capacity should be achieved.

The permeability trials conducted exhibit how k_v as a function of FL can be extracted in a controlled experiment. Being a free draining material (void ratio of type B material measured to range between 0.66 and 0.80) with a large void space, a major drop in permeability values (and thus drainage capacity) is expected only when fouling extent reaches significant levels within the trench. A foulant-dominated fill will be one for which the drainage capacity will be a function of the foulant rather than the aggregate fill ($k_v < 5 \text{ mm/s}$, $R_{FV} < 0.6$). Its functionality will thus be hindered and the removal of surface or subsurface water will be reduced. We can thus establish certain boundaries between discreet condition states, and these are presented (in a qualitative manner) in Table 1 linked to anticipated FL

Condition band	Condition criteria		Anticipated performance	
	Surface	Subsurface	Surface	Subsurface
1. EC	Highly porous (minimal to zero FL)	Highly porous (minimal to zero FL)	Free draining	Free draining
2. FC	Highly porous (minimal to moderate FL)	Highly porous (minimal to moderate FL)	No impact on drainage performance	No impact on drainage performance
3. FCC	Reduced porosity (moderate to high FL)	Highly porous (minimal to moderate FL)	Reduced water removal capacity	No impact on drainage performance
4. PC	Minimal porosity (high to very high FL)	Minimal porosity (high to moderate FL)	Minimal water removal capacity	Minimal water removal capacity
5. PCC	Foulant-dominated fill	Minimal porosity (high to very high FL)	Zero water removal capacity	Minimal water removal capacity
6. VPC	Foulant-dominated fill	Foulant-dominated fill	Zero water removal capacity	Zero water removal capacity

Tab 1 HFD discreet condition bands and condition criteria and anticipated drainage performance

Employed with an HFD generic ageing/renewal model, asset owners can assess and characterise filter drain sections within an evaluated network according to quantitative fouling and performance levels. In line with PMS presented in previous sections, to add value to this model, a mathematical representation of ageing and renewal policies should be considered.

In its simplest form, a generalised deterioration/renewal mathematical model conceptualised by De La Garza and Krueger (2007) is depicted in Equation 2. In principle, the model determines the annual change in the asset condition by calculating the effects of maintenance treatments on the various condition levels and then ageing the resulting condition distributions according to the adopted deterioration rates.

$$\begin{aligned}
 & \text{Condition}_j(t + 1) \\
 &= \text{Condition}_j(t) - \frac{\text{Condition}_j(t)}{D_{jk}} + \frac{\text{Condition}_i(t)}{D_{ij}} + \sum R_{kj}(t) \\
 & - \sum R_{ji}(t)
 \end{aligned}$$

Deterioration rates (denoted by D_{ij} and D_{jk}) can be extracted using either probabilistic or deterministic means, while R_{kj} and R_{ji} denote the upstream condition changes due to maintenance interventions (i.e. the impact of maintenance options on condition states). Focusing back to HFD management requirements, the impact of treatment options on condition states (R values) and a methodology to predict deterioration (D values) using the proposed condition classification framework (Table 1, Figure 4) should be defined.

An example of such a work in the sector has recently been presented by Costello et al. (2011), which describes a DST for managing ancillary assets using proactive principles. The methodology in this work draws from standard inventory collection practices and adopts five discreet condition bands and probabilistic Markov chains to simulate the deterioration of the assets (and to tackle the absence of historic condition data reported in the work). Once the required data for year one is collected (using a simplified CAS), a base condition vector is established to describe the condition distribution of assets within the network with bands

ranging between excellent to very poor. The authors then calculate and present deteriorated states (the ageing process) using a transition probability matrix throughout the planning horizon in a given network. Having no records of deterioration rates, engineering judgement is used and a linear model to set up a life-cycle planning model is defined.

Looking back to HFD deterioration understanding, empirical evidence suggests a larger than 10-year operational life (reported to extend past the 20-year mark in some cases). Similar to the ancillary assets case, the typically reactive HFD management approach falls short in terms of enabling the collection and use of relevant condition information that could be embedded in a deterioration model (and thus allow the extraction of relevant D values as per De La Garza and Krueger, 2007). To enable a network level evaluation of HFD and predict the condition of the drainage network in discreet condition bands, a Markov probabilities transition matrix is proposed to represent ageing in a defined network. The six condition states (n-EC, FC, FCC, PC, PCC, VPC) introduced in this work (Table 1) are adopted, and an asset life (L) equal to 25 years is used; lastly, the deterioration is assumed to progress in a linear manner. The calibration and the level of accuracy of such a probability matrix will inevitably be a result of the collection of annual network-level condition data.

Using this scenario and adopting a base condition vector to denote 100% of the HFD network to lie within the excellent condition band (year 0), the progression of deterioration can be extracted for the whole network using the transition probabilities (extracted using Equations 3a, 3b). This is done by basic matrix manipulation; to extract the first year's deteriorated vector (a_1), one needs to multiply the base condition vector ($a_0 = [1, 0, 0, 0, 0, 0]$) with the probability matrix P; to calculate the condition distribution at any future year, $a_t = a_{t-1} P = a_0 P^t$ can be used.

$$P = \begin{bmatrix} p_{11} & p_{12} & \cdots & p_{1n} \\ p_{21} & p_{22} & \cdots & p_{2n} \\ \vdots & \cdots & \ddots & \vdots \\ p_{n1} & p_{n2} & \cdots & p_{nn} \end{bmatrix} = \begin{bmatrix} 1 - 2a & a & a & & & \\ & 1 - 2a & a & a & & \\ & & 1 - a & 0 & a & \\ & & & 1 - 2a & a & a \\ & & & & 1 - a & a \\ & & & & & 0 & 1 \end{bmatrix}$$

Adopting the transition probabilities matrix (TPM) and using the parameters described in the previous paragraphs, one can graphically represent the deterioration of HFD in a given network as shown in Figure 5.

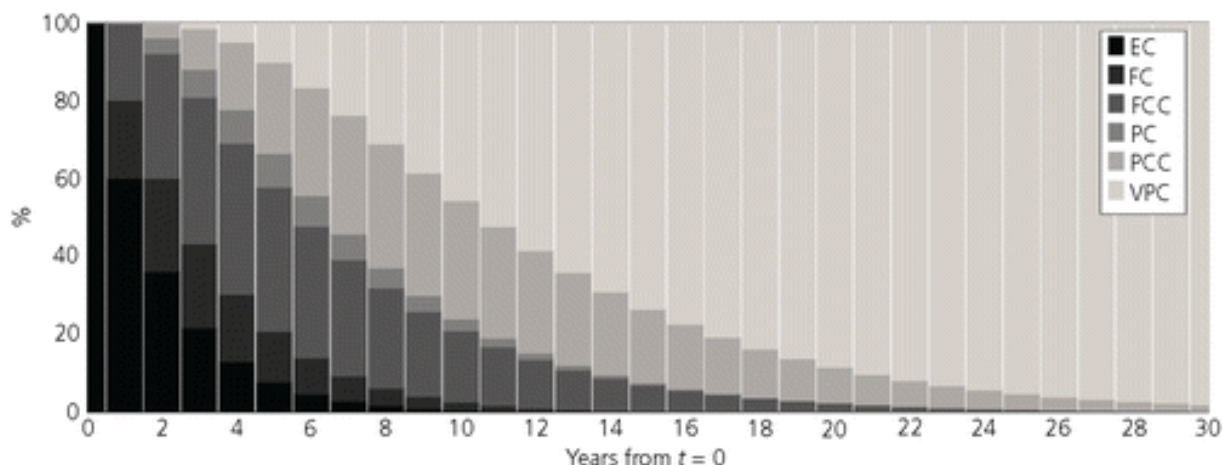


Fig 5 Distribution of HFD network condition bands adopting $L = 25$ and linear deterioration progression

3.6 DEFINING A PRAGMATIC HFD DST

Central to AM systems are asset renewal and replacement analysis methods. These are economic efficiency assessments of the impact of all M,R&R actions to exhibit the effect of intervention strategies on the asset's future condition (the positive effect of maintenance) mapped against anticipated project costs. This will allow the development of a multiyear HFD maintenance programme for an entire road network.

Figure 5 represents HFD ageing (at the network level) assuming no maintenance interventions during a 30-year period; it is a graphical representation of how year 0 condition distributions in the network (denoted by the base vector a_0) are projected in a specified planning horizon using the TPM proposed in Equation 3b. When interventions are to be taken into account, a DST is essential to dictate how and when maintenance is triggered, how investment scenarios should be formulated and what strategies are to be selected. By taking current and future condition data into account (assuming the Markov process can be used to model the deterioration process), asset owners adopting a DST will be able to address

- What is the cost of to-date deferred maintenance (current maintenance backlog)?
- What are the remaining service lives?
- What should be prioritised?
- What is the optimum maintenance strategy to be formulated for a defined planning horizon?

The structure of such a DST can be seen in Figure 6. The tool requires the definition of a clear system objective which can be the maximisation of HFD network performance or minimisation of maintenance costs over a planning horizon. The proposed DST uses such inputs as inventory and condition data, deterioration models and maintenance options impacts and unit rates. By embedding performance targets and constraints (financial or minimum

condition based), asset owners and managers will be able to establish rational and targeted maintenance scheduling at first, and eventually, optimal lifecycles and long-term investment planning.

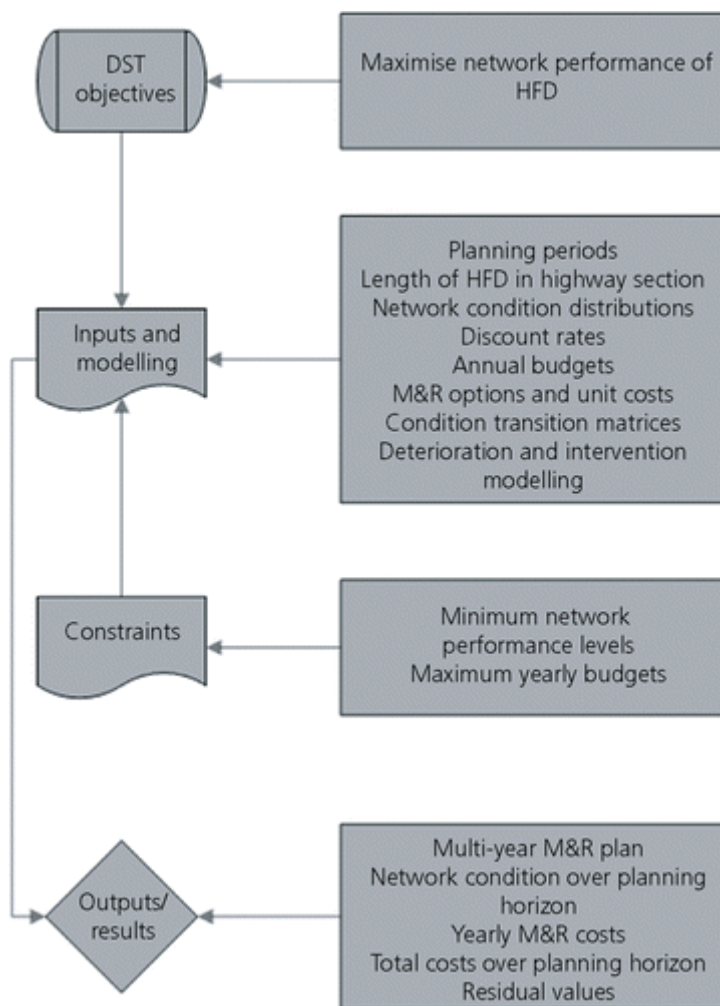


Fig 6 DST structure adopted by Wong et al. (2003) and modified for HFD MS

4 CONCLUSIONS AND RECOMMENDATIONS

AM strategies have given rise to sustainable management of transportation assets in recent times. This paper suggests that drainage should be embedded in AM systems (or drainage management should adopt AM thinking) and a rational approach to establish proactive means to manage HFD should be formulated. Current practices tend to ignore the collection of relevant information to enable the use of such an approach, and focus instead on reactive or risk-based philosophies that often translate to incurred costs to both road operators and road users.

Existing maintenance thinking and AM strategies have been evaluated through available guides and relevant publications, and the need to address a number of HFD-specific issues has been identified. The fact that strategic AM documents introduce only the fundamental concepts to be developed and drainage-related literature is limited and insufficient to support the prerequisites for holistic management suggest the need to address the following questions

- What kind of HFD data are to be collected?
- How are these to be used?
- In what sense will the outputs reinforce the case of AM and be of true value?

The paper has focused on conceptualising the engineering end of AM by introducing HFD condition metrics and tools to project ageing and deterioration (using a Markov TPM) and a DST framework that could enable road engineers to monitor life-cycle costs by embedding the aforementioned management elements.

By defining two distinctive HFD failure modes and the resulting functional impairment, a general ageing/renewal model has been conceptualised. Mapped to a deterioration mathematical model, six discreet condition bands to represent the ageing of the asset have been introduced. Looking at the limited field evaluations and the existing historical data available (primarily empirical network understanding), it is proposed that current projections of HFD service lives underestimate the capacity of the asset to operate at acceptable service levels.

While based on engineering judgement and limited field and laboratory evaluations, a rational (and network specific) approach to classify the performance of the asset is proposed (also recognising the need to separate the surface and subsurface functions of the drain). The condition and performance information to be collected should provide the quantitative basis for informed maintenance planning; this thinking can address the need to assess the physical condition, level of service and the effect of proposed treatment options of HFD in a specified planning horizon, while focusing on easily attainable and processed management data.

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APPENDIX C A CONDITION ASSESSMENT APPROACH FOR HIGHWAY FILTER DRAINS USING GROUND PENETRATING RADAR (PAPER 3)

Full Reference

Stylianides, T., Frost, M.W., Fleming, P.R., Mageean, M. and Huetson, A., 2016. A condition assessment approach for highway filter drains using ground penetrating radar. *Procedia Engineering*, 143, pp.1226-1235

Abstract

The deterioration of highway filter drains (HFDs) is driven by the intrusion of foreign particles within the drainage trench. Being a porous material that offers high water removal capacity at the beginning of its service life, the drainage performance of the backfill can be significantly reduced in time by the introduced fouling material. This poses a serious safety hazard for road users (standing water on the carriageway), and can potentially have an effect in the structural capacity of the pavement. With currently limited approaches to methodically evaluate the physical condition of such assets, the Ground Penetrating Radar (GPR) offers an effective, non-destructive and continuous way to achieve this at both the project and network level. The laboratory calibration study carried out to support its adoption in a condition assessment system, builds upon the evaluation of a HFD-specific condition index aligned to permeability trials and the extraction of dielectric properties of the granular backfill material at different fouled states. The paper thus discusses what kind of HFD distress information are to be collected (condition data) and how this can be achieved (data collection methods), and defines four distinctive HFD media condition bands (Excellent to Very Poor) based on the proposed free voids ratio (R_{FV}) ranges and extracted relative permittivity values

Key words

Highway Filter Drains, Ground Penetrating Radar, Condition Assessment, Permeability, Fouling Index

1 INTRODUCTION

The deterioration of highway filter drains (HFDs) is driven by the intrusion of foreign particles within the drainage trench. Being a porous material that offers high water removal capacity at the beginning of its service life, the long run performance of the backfill can be severely reduced by the introduced fouling material. This manifests as a serious safety hazard for road users (standing water on the carriageway), and can potentially have an effect on the structural capacity of the pavement.

With no formal frameworks currently in place to allow the assessment of the physical condition of in - service HFD and thus to enable holistic management of the drains, this paper investigates the condition data required and the means to collect them in order to support proactive and condition-driven HFD management. The aim of this work is to present a quantitative metric that can be used to assess the physical condition of HFDs and the tools being developed to enable the collection the aforementioned metric (or distress scale).

A laboratory-based evaluation of the HFD deterioration characteristics is hence described building upon large scale permeability trials (linking the proposed fouling metric to anticipated levels of drainage capacity) and the use of a non-destructive evaluation technology (namely the Ground Penetrating Radar - GPR) to introduce the means for a network level condition evaluation approach. The combination of the two experimental studies addresses the deterioration of HFDs and aims to define condition data collection and particularly:

- What is to be measured.
- How can this be measured?

2 BACKGROUND

2.1 HFD FUNCTION, DETERIORATION AND CONDITION ASSESSMENT PRINCIPLES; DEFINING THE BASIS FOR ENGINEERED MAINTENANCE PLANNING

Highway filter drains are aggregate filled trenches fitted with a porous carrier pipe at the base used to drain significant lengths of the UK highways network. The granular material used, which is typically (but not restrictively) exposed at the surface of the trench, allows for efficient removal of pavement run-off due to its high porosity. It also enables the removal of subsurface water from the pavement foundation and structural layers. Such (combined) systems can be advantageously employed in cuttings, which require significant ground water removal. The drains are constructed in verges and/or central reserves adjacent to the low edges of pavements enabling surface water to run off the pavement directly onto the trench and then permeate through the aggregate backfill to the drainpipe at the base of the drain.

The deterioration of the particular drainage asset is caused by the accumulation of introduced particles (fouling material) within the filter media during its operational life. A number of studies have been conducted in the past to address deterioration of such drains but these often provide information related to the fouling composition found in trenches without really addressing the question of managing maintenance operations and defining condition

assessment principles (Samuel & Farrar, 1989; Samuel & Farrar, 1988). Current design-life projections suggest the aggregate fill will reach a poor state after 10 years of operation requiring replacement at that point.

From site observations and empirical understanding of the asset's long-term performance, if introduced fines fill up the available void space in a trench, the drainage capacity of the material may drop significantly. Depending on the progression of this type of deterioration and the concentration of fouling at either the uppermost or basal sections of a HFD, two distinctive failure modes can be identified. The first, more related to the surface-water removal capacity, manifests when a cohesive and often impermeable (when compared to the initially free draining backfill) crust forms at the surface of the trench which limits the free flow of runoff from the carriageway down the trench. Water is re-directed back to the pavement surface resulting in 'spray' and potentially wet-skidding accidents attributed to hydroplaning (Black & Jackson, 2000).

It is widely recognised that the presence of excess moisture in pavement layers can reduce the structure's service life. Deteriorated HFDs may be unable to cope with rising groundwater tables and allow water to reach the pavement subgrade from various sources (pavement edge, surface discontinuities, water table, and high ground). The second failure mode related to a gradual 'bottom-up' deterioration of the fill may lead to a HFD section that fails to remove sub-surface water and surface runoff from the pavement system and thus reduce the structural capacity of the courses affected. Excess water may lead to a number of failure modes and road engineers usually aim to reduce water problems by eliminating water infiltration (through the wearing courses) and to design drainage systems that enable quick removal of water from the structure.

If fouling levels as a direct measurement of HFD deterioration can be linked to performance levels, a condition evaluation framework accountable for the asset's degradation characteristics can be established (Stylianides, et al., 2015a.). The methods of collecting the condition data should then be addressed in a way that reinforces asset management (AM) principles and allows the identification of drainage assets that offer low levels of service, the subsequent determination of the maintenance backlog and the definition of intervention planning and treatment options.

With conventional HFD condition assessment thinking (and lacking any official evaluation framework) data for condition evaluation can be obtained from predetermined test sections or through visual inspections. Both means will fail to address fouling levels and hence deterioration extent in a quantitative manner. The former option will inevitably enable only discrete data evaluation (for an asset that usually spans over many kilometres), or costly and time demanding sample collection and sieving / sorting. The latter is based on rating rather than measuring, and bound to provide subjective results (Stylianides, et al., 2015b.). Since no holistic condition assessment approach has been proposed to date, the adoption of a non-destructive testing / evaluation (NDT) technology that has the advantage of rapid and continuous assessment of linear assets is proposed and presented in the following sections.

2.2 GPR FUNDAMENTALS; PAVEMENT AND RAILWAY APPLICATIONS

A NDT option that has been adopted in various highways and transportation related condition surveys and is being supported by a vast number of pavement (Evans, et al., 2008) and ballast (Leng & Al-Qadi, 2009; De Chiara, et al., 2014; Al-Qadi, et al., 2010; Kashani, et al., 2015) laboratory or field studies, is the GPR. Elements of the supporting literature (and of the current practice), pertaining to the evaluation of layer thicknesses in pavements or the identification of spent ballast in railways studies using this technology, show potential in respect to identifying and proposing a condition data collection methodology for HFD ad-hoc conditions.

The GPR is a sub-surface sensing technology introduced in the early 1970's used for both shallow and deep investigations and has since grown in use in the highways and railway sectors. Three electrical properties pertaining to material characteristics govern the propagation, attenuation and scattering/reflection of the electromagnetic pulse through a medium, namely magnetic susceptibility (or permeability) - (μ), electrical conductivity (σ) and lastly relative permittivity (ϵ). Interchanging electrical properties within an evaluated medium cause significant reflection events of the incident wave. As the electromagnetic pulse is radiated from the GPR, it travels vertically through the medium under evaluation at a velocity (u) which is primarily a function of the permittivity value (and of the speed of light in vacuum $c = 0.3 \text{ m/ns}$) according to:

$$u = \frac{c}{\sqrt{\epsilon}} \quad (1)$$

The wave spreads out and travels downwards until it reaches an object (or a stratigraphic layer) that has different electrical properties than the host layer, at which point the wave is reflected and evidence of its reflection is detected by the receiver. Such differences can be a result of moisture or density variations or even the presence of a different material in the evaluated section (i.e. a wave propagating through a dry gravel layer through to a wet sand layer) (Daniels, 2000). The amount of energy reflected will be a function of the reflection coefficient γ , which is defined according to:

$$\gamma = \frac{\sqrt{\epsilon_2} - \sqrt{\epsilon_1}}{\sqrt{\epsilon_2} + \sqrt{\epsilon_1}} \quad (2)$$

where ϵ_1, ϵ_2 correspond to the dielectric constants of the material the wave is exiting from and the one it is entering to respectively. As a result, reflected energy will reach the receiver at different times as a function of the dielectric constant of the materials met in the EM wave propagation path. The amplitudes are then recorded and plotted as a function of time (or depth if the dielectric constant can be measured or estimated) and a GPR trace is generated.

The most common property evaluated in practical applications of the GPR (in both pavement and railway track-bed investigations) is the relative permittivity (ϵ) or 'dielectric constant' (κ) as is often referred to in literature. The permittivity of subsurface materials may vary dramatically, especially in the presence of free water ($\epsilon_{air} = 1, \epsilon_{granite(dry)} = 5, \epsilon_{clay} = 5 - 40, \epsilon_{water} = 81$ (Saarenketo, 2006)▯). If the thickness of the evaluated medium is known or easily identified with practical means, information regarding the intrusion of fines (in a ballast layer) or water (in ballast / pavement) in the same medium can be extracted. This is particularly important in railway condition surveys as the measured relative permittivity is often used to infer a level of ballast fouling (extent and level of deterioration of the section) and 'engineer' the maintenance planning process. In general, higher values of measured ϵ are

indicative of increased levels of ballast deterioration (Leng & Al-Qadi, 2009); for pavements, steep increases or discontinuities of the same value may suggest the presence of excess water in the pavement system or foundations (Benedetto & Pensa, 2007). The other way around, if the dielectric constant of a specific material is known, the thickness of a layer (r) comprised of this same material, can easily be calculated based on the signal's two-way travel time (Δt) using

$$r = \frac{(u \times \Delta t)}{2} = \frac{c \times \Delta t}{2\sqrt{\epsilon_r}} \quad (3)$$

3 METHODOLOGY

The following methodology describes the condition metric devised for ad-hoc HFD design and deterioration characteristics, and the means to evaluate it non-destructively. The condition assessment approach builds upon two discrete pillars: the adoption of condition indices aligned to permeability trials (the means to assess the physical condition and infer a level of performance) and the extraction of relative permittivity values of the granular backfill material using a ground coupled 1GHz antenna (the tool used to carry out the condition assessment).

3.1 WHAT TO MEASURE; FOULING SCALES AND DRAINAGE CAPACITY

The large-scale permeameter allows for the measurement of hydraulic conductivity values of samples with a radius of 375mm and depth of 450mm with varying fouling levels under a relatively low constant head. Vertical hydraulic conductivity values (k_v) of different aggregate-foulant mixes are extracted and are used to simulate and define discrete condition states representative of fouling levels mapped to an anticipated level of drainage performance. k_v values are then normalised using an assumed $k_{vmax} = 50 \text{ mm/sec}$ (this extracted by considering the non-linear increase of k_v with decreasing levels of fouling and the maximum recorded $k_v \approx 39 \text{ mm/sec}$ at low levels of fouling– see Figure 4).

Water is initially used to fill up the tank and measurements of flow are completed once samples are fully saturated. A constant flow is achieved using a weir at the top of the tank and the permeability at each fouling state is extracted by measuring the trial time and flow for each test and adopting Darcy's Law.

The filter material used is Type B (BSI specifications) aggregate (or 20-40mm stone as commonly referred to), and the fouling mix is designed in such a way as to represent the fouling retrieved from site evaluations conducted in the past (Stylianides, et al., 2015a.). The index used to represent the changing status of the aggregate fill in the study is a volumetric index formulated adopting simplistic material properties and normalising the data according to the filter's 'fresh' available void space. This (the free voids ratio, R_{FV}), is a further development to the metrics presented in Stylianides, et al., (2015a.) and modified to better represent the deteriorated backfill aligned to the particle matrix anticipated to have an effect in the vertical permeability (k_v) of the evaluated aggregate-fouling mix. While limited field evaluation studies have been (to date) presented targeting HFD deterioration, defining a

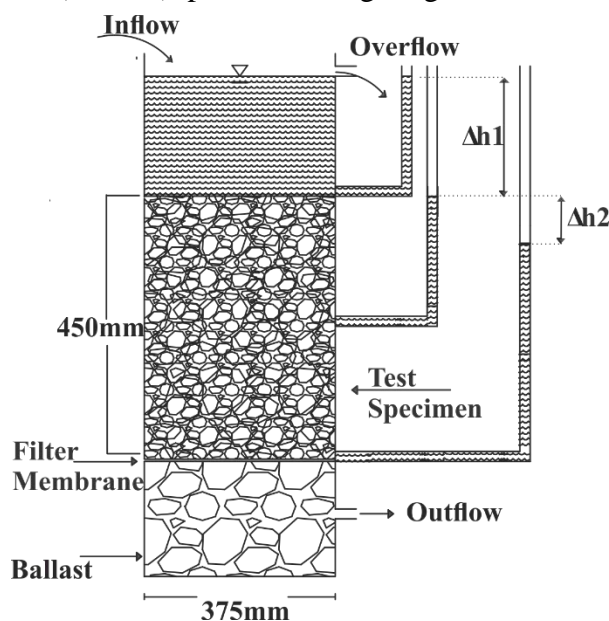


Figure 1: Schematic of large-scale permeability tank used in laboratory trials

distress index can be achieved by building upon relevant ballast evaluation studies (Indraratna, et al., 2011; Anbazhagan, et al., 2012) and adopting basic engineering judgment. The particle matrix comprised by the fouling mix below 8mm is thus selected to represent the introduced material in trenches (fouling). The formula used to represent the index 'Free Voids Ratio' in this case is:

$$R_{FV} = \frac{V_{VFRA} - V_F}{V_{VFRA}} = \frac{e_{fr}V_A - \frac{M_F}{\rho_f}}{e_{fr}V_A} = \frac{e_{fr} \frac{M_A}{G_A} - \frac{M_F}{\rho_f}}{e_{fr} \frac{M_A}{G_A}} \quad (4)$$

V_{VFRA} is an estimation of the volume of voids in a fresh backfill while V_F represents the volume of the fouling material. The former is calculated using e_{fr} , the void ratio for fresh Type B aggregate, adopted here to be equal to 0.65. This value can range between 0.6 and 0.8 as extracted in laboratory trials and for in-situ evaluations it will depend on the particular gradation characteristics of the HFD backfill used and the levels of compaction achieved (Type B material is defined using a gradation envelope in design standards thus minor deviations from the proposed e_{fr} are anticipated). The material's specific gravity G_A is again extracted in the laboratory while ρ_f , defining the bulk density of the foulant, is measured to be equal to 1.5 tons/m³. This value has been derived using the engineered fouling material used in this study and a number of compaction tests. In simple terms, Equation 3 represents a normalised estimation of the available void space in a HFD medium and can be accountable for condition information extraction as seen in the experimental trials section below.

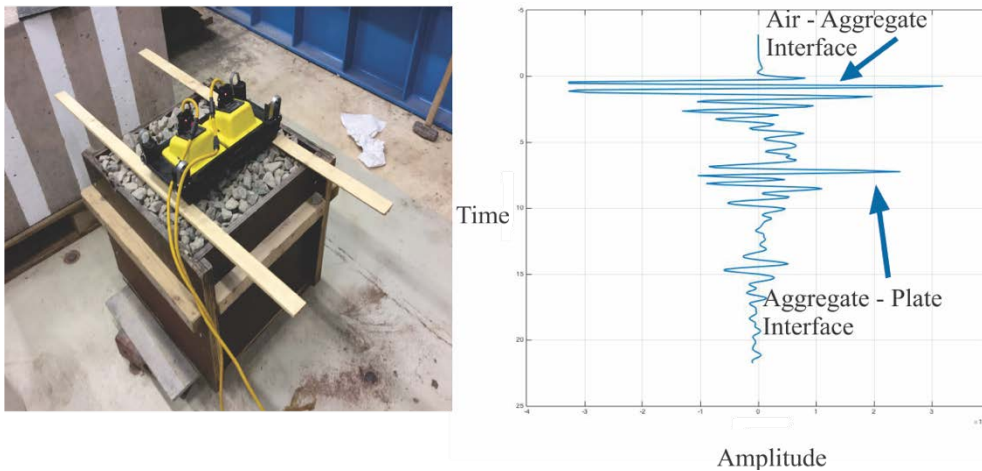


Figure 2: Container, 1GHz EkkoPulse antenna and typical unprocessed A-scan

3.2 HOW TO MEASURE IT; NON-DESTRUCTIVE EVALUATION AND DIELECTRIC DISPERSION STUDY

For this set of trials, a 0.5 × 0.5 × 0.5m container is used to extract dielectric permittivity values by evaluating propagation velocities between known interfaces in the signal's time domain. To distinguish between the required interfaces, a perfect reflector (steel plate) is positioned at the bottom-end of the tank. Figure 2 exhibits the general setup, the ground-coupled EkkoPulse GPR used for this set of trials and a time-domain waveform that depicts

typical material boundaries in a NDT trial. The container is built using nominal metallic elements to minimise any interference or noise in the extracted and processed A-scans.

Three types of fouling material are adopted here; a clay and a sand based, and an engineered foulant (*CF, SF, EF* respectively), to match in-situ fouling conditions. The aim of this element of the work, is to study how the dielectric constant can be extracted and highlighted for materials with different fouling and moisture levels that may replicate in-service deteriorated HFD sections. The GPR used in the study is a ground-coupled system with an antenna of 1GHz central frequency.

The tank is initially filled with the aggregate material simulating a 'fresh' fill. Once data collection is completed for a particular aggregate-fouling trial, fouling material (sand or clay or the combination of the two) is introduced in the container and mixed in the aggregate



Figure 3 Representation of 3 fouling states using $R_{FV} = 100\%$, $R_{FV} = 50\%$ and $R_{FV} = 0\%$:

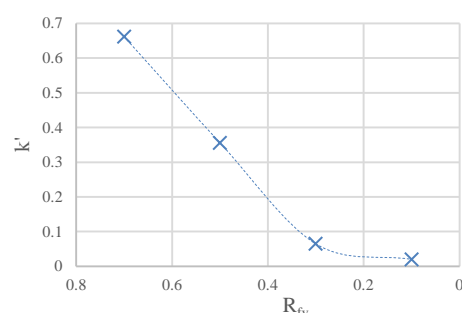


Figure 4: Variation of normalised permeability as a function of R_{FV}

sample using a pneumatic drill to change the fouling status of the following trial. Material interfaces are identified using a time-domain waveform and the dielectric permittivity values are calculated based on the fill's depth and the wave's two-way travel time (Δt [ns]) using Equations (1) and (3). Permittivity values are also extracted at different moisture content levels at fresh and highly fouled states using the available foulants. To achieve this, water is added in the tank and allowed to evaporate naturally; gravimetric water content (GWC) is then measured for each sample.

4 RESULTS

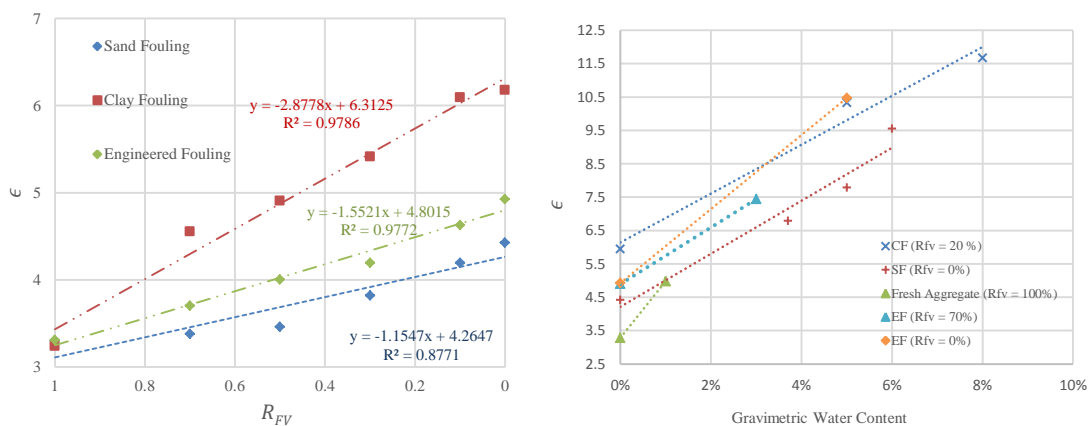
4.1 CONDITION METRICS AND DRAINAGE CAPACITY

By linking the proposed fouling index to the physical condition of the HFD backfill, a swift evaluation of conditions can be extracted (see Figure 3). In this method, a handful of simple properties of the filter media aggregate and foulants require measuring. The approach is practical and pragmatic and is in fact the first quantitative approach in classifying and evaluating the deterioration characteristics of the aggregate backfill. Using R_{FV} , one can draw conclusions regarding the drainage performance of the HFD backfill and establish discrete asset condition bands if the index is then mapped to a series of permeability trials to measure the anticipated drainage performance drop.

Figure 4 presents this illustrating the normalised vertical permeability value of the fill ($k' = k_v/K_{vmax}$), extracted as a function of the free-voids ratio. Below $R_{FV} = 0.3$, it can be assumed that the material becomes foulant - dominated and presents extremely low (normalised) permeability values; in principle this will result in low levels of performance and will be indicative of a HFD section that can be considered as 'spent'. While for in-service conditions there will be a number of parameters to factorise when drainage performance of a pavement section is considered, the vertical hydraulic capacity of the aggregate fill can be used to predict the anticipated 'drainage efficiency' of a particular HFD trench.

4.2 GPR CALIBRATION STUDY

The electrical alterations caused by introducing sand, clay and the engineered fouling material along with moisture within the trial tank, cause distinctive reflection and propagation variations that are easily identified in a typical time-domain waveform. Material boundaries can easily be extracted (as seen at Figure 2), due to the anticipated large peaks at air - aggregate and aggregate - steel plate interfaces, using simple post-processing filtering (time-zero correction and bandpass butterworth within the time domain). Figure 5 exhibits how ϵ varies as a function of fouling types and levels. The use of clay fouling results in higher permittivity values and in general terms, a reduced R_{FV} results in lower wave propagation velocities in the evaluated medium and thus higher extracted values of ϵ .



Moisture content plays a significant role in the GPR calibration study. Figure 5 also presents permittivity values as a function of water content for samples with different fouling conditions. It is clear that with increasing moisture levels, the permittivity values of the aggregate-foulant mix shift to much higher levels even in cases of generally low fouling content. At $GWC = 3\%$ and $R_{FV} = 70\%$, using the engineered fouling material, $\epsilon = 7.43$. At

$R_{FV} = 0\%$ for a dry, sand-fouled sample $\epsilon = 4.42$; the value moves up to $\epsilon = 9.54$ for $GWC = 6\%$ for the same type and extent of fouling.

It can be generalised that high extracted permittivity values during a condition survey can be attributed to a combination of fouling levels and moisture content. With increasing clay content in the fouling mix, the parameter gets even larger but the data suggests that the wave velocity is more sensitive to moisture rather than fouling levels (or types). The highest extracted permittivity $\epsilon = 11.67$, occurs at $R_{FV} = 20\%$ using clay fouling and an extracted gravimetric water content of 0.08. Compared to fresh aggregate ($\epsilon_{fresh} = 3.28$) this is the largest deviation of relative permittivity recorded in this study even though higher values should in principle be extracted with increasing levels of moisture or fouling in a HFD trench

5 CONCLUSION

A laboratory study has been conducted to introduce a condition assessment methodology for the aggregate backfill of HFD. The study revolves around two main axes: the identification of relevant condition data, and the introduction of a non-destructive method to collect this data. The paper thus presents the alignment of a proposed distress classification index, R_{FV} as a normalised volumetric quantification of foreign material in a trench, to a level of anticipated performance ($k' = k_v / (k_{vmax})$), as a measurement of normalised vertical permeability of the aggregate fill and then to a range of dielectric constants for aggregate fills at varying condition states. It is shown how the hydraulic permeability of the aggregate backfill reduces with increasing fouling levels ranging from a normalised value of 0.67 to one of 0.02 for a range of R_{FV} [0.7 0.1].

Table 1 brings the fouling index, performance levels and dielectric evaluation information together (focusing on ϵ for dry conditions), and offers a classification approach with four condition bands that range from excellent, to spent aggregate fill. This should address the two main questions raised in Section 1 (what to measure and how to measure it).

Condition Band	R_{FV}	$k' = \frac{K_V}{K_{max}}$	ϵ dry
As new - Excellent	$R_{FV} > 0.7$	$k' > 0.6$	$\epsilon < 3.7$
Good	$0.7 < R_{FV} < 0.5$	$0.6 < k' < 0.35$	$3.7 < \epsilon < 4$
Poor	$0.5 < R_{FV} < 0.3$	$0.35 < k' < 0.05$	$4 < \epsilon < 4.2$
Very Poor - Spent	$R_{FV} < 0.3$	$k' < 0.05$	$\epsilon > 4.2$

Table - 1 Setting discrete condition bands and linking R_{FV} to K_V and ϵ

The permittivity dispersion study suggests that water will be the parameter that defines the propagation velocity of the radio-waves in the filter medium and it cannot be ignored in a condition evaluation study. In fact, while water content can be loosely linked with fouling levels (in general terms, higher fouling levels can be indicative of higher levels of retained water and vice-versa) this won't always be the case on site. Fouling-free, wet aggregate for example, can have a significantly larger permittivity value than in its dry state ($\epsilon_{aggwet} =$

4.97 - $\epsilon_{aggdry} = 3.28$) and as such, a trench could falsely be identified as highly fouled or spent. In brief, condition surveys completed in wet periods can lead to false results and unnecessary maintenance planning if the causes for the decreased wave propagation velocities in the filter medium are not properly identified and taken into account. It might thus be reasonable to target HFD condition surveys during dry periods and calibrate the GPR response by extracting targeted samples from drainage trenches to correlate also for moisture content in the drainage trench.

A linear relation can be extracted from the presented figures linking the incremental increase of ϵ as a function of R_{FV} but further validation and calibration of the GPR data collection method and processing techniques is required before full-scale condition surveys can be undertaken. Further work packages planned include elements of additional testing and data processing (employing evaluation approaches based on analysis from void scattering and the frequency domain) to enable enhancement of the condition data collection method.

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APPENDIX D GEOPHYSICAL INVESTIGATION OF HFD; EVALUATION METHODOLOGIES USING GPR (PAPER 4)

Full Reference

STYLIANIDES, T., FROST, M.W., FLEMING, P.R., MAGEEAN, M., 2016 Geophysical investigation of Highway Filter Drains; condition evaluation methodologies using Ground Penetrating Radar [in progress]

Abstract

Highway Filter Drains (HFDs) are combined drainage systems used in the UK to drain long lengths of the road network. Often deteriorating at rates asset managers fail to comprehend, focus has recently been shifted in establishing means of proactively assessing the asset's degraded characteristics. With no evaluation protocols in place to collect condition data at the network or project level, the current state of practise restricts HFD investment planning, prioritisation or maintenance backlog estimation. The use of the Ground Penetrating Radar in the transportation infrastructure sector has generated in recent years significant value from condition surveys in both Highway and Railway studies. This paper presents current data collection and processing thinking used in the two fields; it then describes a laboratory based study that builds upon data collection and processing approaches derived from either track-bed or pavement surveys in order to identify the prerequisites for in-situ non-destructive HFD condition evaluation

Keywords

Highway Filter Drains; GPR; Pavement Evaluation; Railway Ballast; Fouling Scales; Void Scattering, Maintenance Management, Short Time Fourier Transforms

Paper Type: Journal Publication

1 INTRODUCTION

Like a number of physical assets in highways infrastructure, filter drains (gravel filled trenches adjacent to the carriageway - HFDs), deteriorate at a rate that asset owners and operators often fail to quantify. Designed to facilitate the fast and efficient removal of surface and sub-surface water from pavement systems, HFDs deteriorate over time as fines and road detritus accumulate in the coarse gravel aggregate backfilled trench, reducing drainage capacity.

To inform and optimise maintenance planning there is a requirement to collect asset condition information that is reliable and reproducible. Traditional condition diagnosis for HFDs is usually limited to either visual assessments of the many-km spanning drains, or intrusive sampling and testing in the form of trial holes that reveal the extent of deterioration at a unique point of the network. The strength of the former approach and at the same time its weakness is the subjectivity of an inspector's analysis. Furthermore, visual assessments are bound to offer information only for the surface layers of the trench. Intrusive testing can in practice be employed only locally at areas of concern as it is limited by the requirement to destructively assess the aggregate backfill (by sampling and sieving) proving to be inefficient in painting the full picture of long spanning linear drains. In both cases no formal condition metrics or assessment protocols have been established to date to physically measure and evaluate the condition of the asset, assess its performance and thus formulate a quantitative network level condition survey methodology that can be routinely and extensively deployed on site.

The authors have already explored the merits of intrusive sampling, sieving and sorting methodologies to quantify the levels of fouling in HFD trenches (Stylianides et al., 2015b, Stylianides et al., 2015a) defining deterioration mechanisms, failure modes and condition indices to be collected. This paper presents an assessment of ground penetrating radar (GPR) processes that can be adopted in network-level non-destructive evaluation of the drains as a means to identify and quantify deterioration characteristics. This was achieved by exploring a number of applications in the transportation infrastructure sector and focusing on pavements and railway track-bed methodologies that can be transposed and adopted for HFD condition evaluation.

The paper thus discusses in the background section, the current service and deterioration understanding and proposed condition evaluation options for HFD. This is then followed by fundamental GPR theory linked to propagation and reflection of electromagnetic waves in different types of medium. This enables the derivation of practical GPR assessment routines often used in practice to characterise and evaluate physical condition, deterioration and quality of a number of transportation assets. Relevant GPR applications (for both pavement and railway track-bed studies) are thus described along with post-processing approaches employed to improve data quality / generated value. Finally, a laboratory-based experimental study developed to extract HFD related condition information based on the above is reported.

2 BACKGROUND

2.1 DETERIORATION AND ASSET AND CONDITION INFORMATION REQUIREMENTS

Highway Filter Drains (HFDs) are used to drain significant lengths of the UK Highways network. They incorporate aggregate filled trenches fitted with a porous carrier pipe at the base. The highly porous uniformly graded granular material, which is typically exposed at the surface of the trench, allows for efficient removal of pavement run-off. The drains also enable the removal of subsurface water from the pavement foundation and structural layers. Such (combined) systems can be used in cuttings, which require significant ground water removal. The drains are constructed in verges and/or central reserves adjacent to the low edges of carriageways enabling surface water to run off the pavement directly onto the trench and then permeate through the aggregate backfill to the drainpipe at the base of the drain.

The deterioration of HFDs is caused by the accumulation of introduced particles (fouling material) from the drained paved area or earthworks within the filter media during its operational life. This reduces the capacity of the drain to remove water and can lead to ponding on the carriageway and consequent safety issues. Farrar and Samuel (1989) and Samuel and Farrar (1988) present studies conducted to address serviceability levels and drainage efficiency of in-service HFDs. These focused on producing information related to the fouling composition retrieved in HFD sections without really looking into the topic of managing maintenance operations against performance or defining condition assessment principles. In fact, the need to manage drainage assets has been a focal point of only limited work in the past. Condition data collection and information management are considered the cornerstone of proactive drainage management and this is evident in recent publications (Spink et al., 2013) nevertheless no engineered condition assessment methodology is described in design standards or good practice guides.

Lacking a proactive, condition - driven management philosophy, current design-life projections suggest that the aggregate fill will reach a poor state after ten years of operation requiring excavation and replacement at that point. Further information regarding what a 'poor state' actually represents is not easily attained; in simple terms, failed states, loss of function, service lives and deterioration understanding are rather generic and remain subjective. Stylianides et al. (2015b) proposed a framework to enable proactive management of the drainage asset, based on collecting relevant condition information related to the extent and level of fouling concentrations in the HFD. This builds upon proposed engineered fouling indices for in-service HFD establishing an inferred relation between a quantified level of undesirable material within a section of drain and a drainability level (a quantitative estimation of a section's drainage capacity).

In terms of asset condition information there is still a requirement to develop a machine-based, network-level data collection approach and Ground Penetrating Radar has been proposed as a suitable tool (Stylianides et al., 2016). The adoption of a non-destructive assessment routine to HFDs requires an understanding of GPR configuration options and data processing methodologies and these are explored in following sections through related pavement and rail-track state of the art and state of practice work.

2.2 GROUND PENETRATING RADAR

2.2.1 THEORY AND PRINCIPLES

Ground penetrating radar (GPR) is an electromagnetic non-destructive evaluation tool with numerous applications in the civil engineering domain (investigation of construction materials, pavements, bridges and railway track-bed). Early applications of the sensing method can be retrieved in literature dating back to late 1950's (El-said, 1956). The GPR has since grown in use in the transportation sector as a means to meet the increasing demand for asset condition and construction information data collection.

As a finite electromagnetic (EM) pulse is emitted from the GPR transmitting antenna, it propagates through the material under evaluation at a velocity that is (Evans et al., 2008) primarily a function of the relative permittivity (ϵ) of the material - often referred to as the dielectric constant. Two more material properties influence the propagation and reflection of a GPR wave, namely (1) magnetic permeability (μ), and (2) electrical conductivity (σ). The relative permittivity ϵ is a complex number expressed in the form:

$$\epsilon = \epsilon' - i\epsilon'' \quad (1)$$

ϵ' defines the real part of the dielectric value and ϵ'' its imaginary component which is linked to the electrical conductivity (σ) according to:

$$\epsilon'' = \sigma / (\epsilon_0) \quad (2)$$

where ϵ_0 denotes the dielectric permittivity of free space equal to $8.85 \times 10^{-12} F/m$.

In a typical application the emitted signal spreads out and travels downward in a medium until it meets an object, or a second medium, that has different electrical properties at which point it is scattered or reflected from the object, and evidence of this is collected by a receiving antenna. As a result, reflections will reach the receiver at different times; the time interval required for each wave to travel from the transmitting antenna, through the medium and a reflection to be picked up by the receiver is called the 'two-way' travel time (Δt). When recorded amplitudes are plotted as a function of time, a GPR 'trace' is generated.

The founding equations used in practical applications of the radar are derived using low-loss material assumptions and ignoring the magnetic susceptibility. The propagation velocity (u) is thus commonly defined using

$$u = c / \sqrt{\epsilon} \quad (3)$$

$c = 0.3m/ns$ and represents the EM wave's travel velocity in air (same as in vacuum) which is equal to the velocity of light. This will be lower when traveling through any medium other than vacuum. The wavelength (λ) of the incident wave inside a medium is related to the frequency (f) and the EM wave velocity so that:

$$\lambda = \frac{u}{f} = c / [f\sqrt{\epsilon}] \quad (4)$$

If the propagation velocity through a given medium can be extracted (or estimated), the medium's depth (r) can be calculated using the recorded two-way travel time according to:

$$r = (u \times \Delta t) / 2 \quad (5)$$

Ground or air-coupled systems have been used in the UK for pavement (Evans et al., 2008) or railway track-bed studies (Brough et al., 2003, Eriksen et al., 2004). Ground systems require the antenna unit to be in direct contact with the scanned medium dictating low survey speeds and even surfaces (thus lane closures and traffic management for pavement studies and risk of damaging the GPR unit in ballast surveys). Air coupled system are mounted at approximately

0.50 m above ground on the back of a survey van to allow for highway-speed surveys and reduce traffic management requirements. The antennae are usually horn shaped and have frequency bandwidths ranging between 500MHz and 2.0GHz that offer different depth penetration capabilities in different materials.

2.2.2 ENGINEERING APPLICATIONS : HIGHWAYS

The application of GPR in pavement diagnostic studies has generally focused the evaluation of as-built conditions (quality control), or the assessment of types and level of distress and deterioration that has accumulated over time. The most common parameters assessed using the radar technology are layer thicknesses, location of voids, steel reinforcement alignment, stripping and general quality control of pavements (Evans et al., 2008).

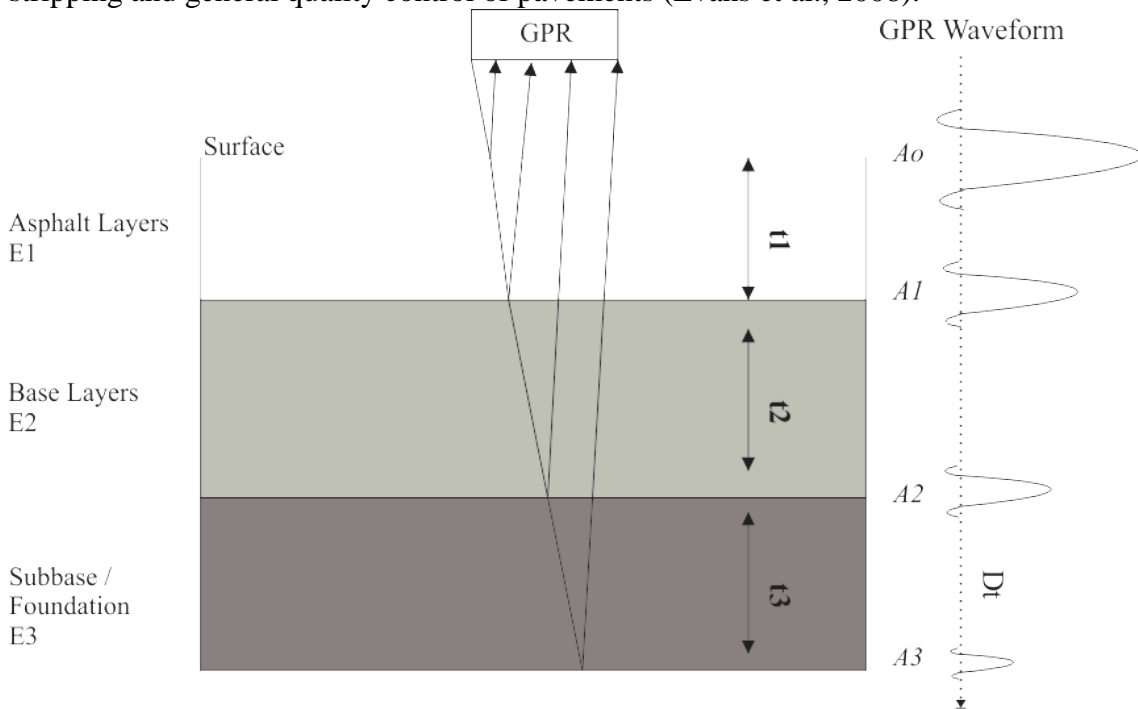


Figure - 1 Typical reflections from layer interfaces in a pavement system; E_i corresponds to dielectric constant of i_{th} layer, t_i to time travelled in layer and A_i to reflection amplitude from interface

Besides measuring the travel time between two reflecting interfaces to identify layer thickness (Equations 3 and 5, Figure 1), the amplitudes of the recorder trace can be used to provide information regarding the dielectric properties of the evaluated medium (Morey and Kovacs, 1977). Assuming that no multiple reflections are picked up in the GPR reflected signal from within the same layer, the relative reflection amplitude of the n_{th} layer can be calculated using:

$$\frac{A_n}{A_{inc}} = \frac{\sqrt{\epsilon_{r,n}} - \sqrt{\epsilon_{r,n+1}}}{\sqrt{\epsilon_{r,n}} + \sqrt{\epsilon_{r,n+1}}} \left[\prod_{i=0}^{n-1} (1 - \gamma_i^2) \right] e^{-n_o \sum_{i=0}^n \frac{\sigma_i d_i}{\sqrt{\epsilon_{r,i}}}} \quad (6)$$

$$n = 0, 1, \dots, N - 1$$

N is the number of layers in the pavement system, A_n the recorded amplitude of the n_{th} layer, A_{inc} is the amplitude of the incident GPR signal measured using a perfect reflector placed on the surface of the pavement (copper or steel). $\epsilon_{r,n}$ is the relative permittivity of the n_{th} layer,

σ_i is the representation of electrical conductivity (assume $\epsilon_{r,0} = 1$ and $\sigma_0 = 0$) and γ the reflection coefficient that defines the amount of energy being reflected between two layers. n_o represents the wave impedance of free space ($n_o = 120\pi\Omega$) (Al-Qadi and Lahouar, 2005b). To calculate the dielectric constant of the first layer $\epsilon_{r,1}$ substitute $n = 0$ and subsequently Equation 7 is reduced to

$$\epsilon_{r,1} = \left(\frac{1 + \left[\frac{A_o}{A_{inc}} \right]}{1 - \left[\frac{A_o}{A_{inc}} \right]} \right)^2 \quad (7)$$

In Popik and Redman (2006a) a discussion of the subsurface imagery obtained from GPR surveys linked to other pavement machine based surveys is presented; the authors identify and discuss work carried out to evaluate concealed repair patches, steel reinforcement location, cracks and joints and lastly pavement layer thicknesses with GPR data showing a good correlation with localised coring. There is though no discussion on moisture content and how data can be skewed with high levels of water in the pavement courses. Li et al. (2010) describe a process to differentiate between various levels of moisture content in HMA layers by identifying that moisture has a strong influence on the dielectric properties of the evaluated courses. Empirical formulae have subsequently been defined linking volumetric water content of HMA layers to a specific range of dielectric constants.

Rodés et al. (2015) base their water content evaluation on the assessment of the frequency spectra of GPR signals aligning the shape of the spectrum and the frequency signature to specific pavement distresses. This approach is however based on a qualitative comparison of the extracted spectra and no further analytical examination is offered to link the spectrum shift with levels of moisture. Further evaluation of the frequency domain is presented in a number of other recent academic studies either targeted at pavement assessment (Benedetto et al., 2012) or material and moisture characterisation in general (Benedetto and Tosti, 2013)

While potential in evaluating the frequency spectrum and the distinctive signature of different road materials and moisture is reported in the state of the (academic) art, there seems to be no clear consensus on a particular methodology to be adopted by the state of practise. Geophysicists and GPR users outside the academic realm tend to follow approaches based on wave travel times and amplitude comparisons to extract the required condition information. Practical applications of the sensing technology are thus anticipated to be sufficiently accurate for layer thickness studies and identification of voids under specific conditions but anticipated to be misleading or biased when moisture evaluation is introduced in the analysis (DMRB - HD 29/08).

2.2.3 ENGINEERING APPLICATIONS: RAILWAYS

The track bed is a structural system of two main superimposed layers, ballast and formation. Ballast often consists of crushed stone whereas the formation layer consists of sand overlaying the subgrade and natural ground. The track material deteriorates gradually with increasing levels of ballast fouling, insufficient lateral confinement and loss of the shear strength of soil due to phenomena of liquefaction and clay pumping (Anbazhagan et al., 2011). The term fouling (or foulants) is used in the field to define quantitatively the contamination of the (initially) uniformly graded, coarse aggregate ballast layer by fines. A detailed break-down of the gradual process (fouling) is presented in a number of publications (Selig and Cantrell, 2001, Sussmann et al., 2012); fines (either generated from within the ballast layer or

introduced in a section) fill up the free voids of the medium leading to poor drainage of the rail track, reduction of vertical resistance and decrease in the movement of particles through the ballast layer. Knowledge of the track's substructure and proper evaluation of its deteriorated characteristics is therefore increasingly considered a prerequisite for maintenance planning renewal strategies. (Eriksen et al., 2006, Selig and Cantrell, 2001).

GPR systems with central antenna frequencies ranging between 400MHz and 2GHz have been successfully used in a number of studies to map ballast quality, determine extent of fouling and generally determine track-bed conditions and moisture presence (Zhang et al., 2011, Carpenter et al., 2004, Hyslip, 2007). Ultimately, GPR users aim to evaluate and align particular characteristics of the reflected wave to ballast specific distress patterns. This has been achieved by either using time domain analysis and often qualitative evaluation of recorded radargrams (Gallagher et al., 1999, Jack and Jackson, 1999), evaluation of the scattering response of the EM signal (Zhang et al., 2011, Al-Qadi et al., 2005) or breaking down and studying the frequency components of the trace (Leng and Al-qadi, 2009b)

2.2.4 ASSESSMENT IN THE TIME DOMAIN

The dielectric constant of the ballast – fouling mix has been proposed as a deterioration indicator for maintenance decision making (Gallagher et al., 1999). Absence of clearly formed basal reflections and wave penetration depth (all decreasing with increasing fines migration through formation (Carpenter et al., 2004)) have also been used as a means of ballast condition assessment (Jack and Jackson, 1999). By identifying the 'footprint' of the fouling material on the EM wave propagation characteristics, dielectric properties of ballast samples in different fouling and water content levels have been extracted in a number of laboratory based studies (Clark et al., 2000, Fontul et al., 2014, Suits et al., 2010). These studies usually draw information from relevant ballast maintenance-management libraries to suggest fouling extent thresholds (aligned to anticipated levels of service) and extract a relevant dielectric constant range to be fitted within these thresholds. Dielectric constants have been found to vary (2 to 4.1 for dry fresh ballast material) based on the aggregate material selected for analysis, levels and types of fouling, moisture content and antenna type and central frequency used in each study (Leng and Al-Qadi, 2010, De Chiara et al., 2014)

2.2.5 ASSESSMENT TARGETTING MIE SCATTERING

Significant reflections arising from within the initially large void space of the ballast medium have been used as an in-situ ballast condition assessment approach (Al-Qadi et al., 2005). Scattering is a process where EM radiation (or other forms of radiation or sound) deviates from its initial propagation trajectory due to irregularities in the propagation medium. When localised objects in a medium are of a size similar to the scale of the EM wavelength, a distinctive scattering response from these objects will be 'amplified' in a typical radar-profile. Three scattering types exist; these are Rayleigh, Mie and Geometric and they depend on the ratio of the wavelength of the incident signal (a function of central antenna frequency) to the circumference of the inhomogeneity in the medium (Zhang et al., 2011).

For ballast layers the 'propagation medium' is assumed to be comprised of the individual ballast aggregate matrix whereas the role of the local scatterers is fulfilled by the available air

voids. The normalised dimension of the air voids (D^N) causing scattering can be found in Al-Qadi et al. (2005):

$$D^N = \frac{\alpha\pi}{\lambda} \quad (8)$$

where λ is the wavelength of the incident wave and $\alpha\pi$ is the circumference of the air void scatterer. When non-uniformities are much smaller than the incident wavelength λ , the scattering response falls within the Rayleigh region. If the object dimension approaches the same size as the excitation wavelength, the response falls within the Mie Region and lastly Geometric scattering occurs if scattering particles are much larger than the EM wavelength. The response enhancement produced through resonance at the Mie region has been identified in GPR scans and has been used as a qualitative or quantitative evaluation of the available void space in a ballast layer in a number of academic publications. In a study presented by Al-Qadi et al. (2010), the application of a trace amplitude envelope is used to extract information from layers that would be missed if a low frequency antenna was selected (a 2GHz antenna is adopted in the study). The authors exhibit how the change of air voids volume in the medium can be used to infer to a degree of fouling in a given section as a function of the ‘intensity’ of the scattering response. The same principles are adopted by Roberts et al. (2007) and Al-Qadi et al. (2008), to present evaluation studies of railroad ballast, subballast and subgrade in either field of laboratory trials proving that the concept may add value to condition assessment studies.

It is though unclear how well understood the approach currently is; in a study presented by De Bold (2011), an effort to quantify the scattering response of ballast layers at different fouled states is described using antennae frequencies ranging from 500MHz to 2.6GHz. The results suggest that scattering of fouled sections is more obvious using lower central GPR frequencies; the same interpretations are described in a follow up study by the same authors (De Bold et al., 2015). In a more recent work (Kashani et al.), the increasing fouling levels are again linked to reduced void scattering using a 2GHz antenna but no further analysis is described to express the decreasing scattering levels due to increasing fouling levels in a quantitative or qualitative approach

2.2.6 ASSESSMENT IN THE FREQUENCY DOMAIN

First introduced for railway ballast applications by Shihab et al. (2002), the signal’s frequency and time domains have been linked to enable condition evaluation of ballast layers adopting Short-Time Fourier Transforms (STFT). The localised frequency properties for a GPR signal are calculated using:

$$STFT_x(t, \Omega) = \int x(\tau)w(\tau - t)e^{-j\Omega\tau} dt \quad (9)$$

where x represents the reflected signal, t the time variable, Ω the frequency variable and w the time window sequence. Breaking down the STFT equation, $w(\tau - t)$ represents the window function signal and $x(\tau)$ the GPR signal in time domain. The Fourier transform of the product of $x(\tau) * w(\tau - t)$ calculates the signal’s frequency energy at time t and frequency Ω . $w(\tau - t)$ represents the window function that has a finite duration.

Only a handful of studies can be retrieved pertaining to the combination of the two domains to extract relevant ballast condition information. These generally suggest that STFT can be an effective method to provide reasonably accurate representations of the levels of ballast fouling or water accumulation (Leng and Al-qadi, 2009b, Leng and Al-Qadi, 2010). The combination of the two domains is reported to also allow for separation of external noise from valuable signal information adding perhaps value to other GPR signal processing approaches (Al-Qadi et al., 2008).

3 EXPERIMENTAL STUDY

The literature presented enables the identification of condition data collection and processing routines derived either for pavement or railway trackbed surveys using the GPR. The sensing tool has been utilised in a number of ways and data processing has been tackled either in the time or frequency domain. The following sections outline the HFD laboratory evaluation study conducted, which is founded upon pavement and railway trackbed non-destructive assessment principles. Data collection and processing routines are presented for artificially deteriorated HFD sections targeting an analysis from void scattering and the application of Short Time Fourier Transforms (STFT) to quantify levels and extent of fouling. Supplementary dielectric evaluation trials are also conducted and implications of fouling levels and moisture are evaluated to present the way forward in terms of holistic non-destructive HFD condition assessment

3.1 METHODOLOGY

Two objectives are defined and evaluated through the laboratory work:

- The evaluation of the electrical properties of HFD aggregate material as a function of fouling types and extent also taking into account moisture in the fill, and
- The application of the two main railway data processing options identified in ballast evaluation studies (analysis from void scattering and the STFT approach).

Two experimental trials were thus designed and conducted to explore the applicability of each method in assessing HFD condition. The first was carried out using a small cylindrical container (360mm deep, 300mm radius – Figure 2a) to enable practical extraction of dielectric constants as a function of changing mix properties. A ground-coupled 1GHz central frequency antenna is used throughout the study and material interfaces are enhanced using a steel plate positioned at the bottom-end of the HFD aggregate. GPR traces (A scans) collected for different fouling states and saved for post-processing with minimal signal filtering used (band-pass butterworth and time zero collection). Wiggle plots are used to estimate two-way travel time of the EM wave in the medium and corresponding dielectric constants of the material.

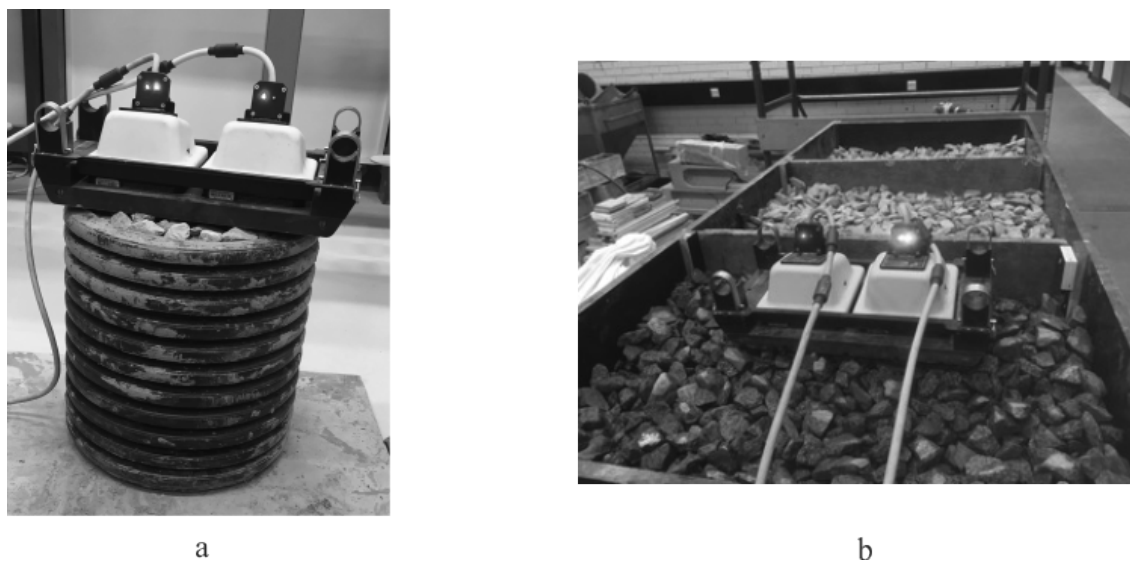


Figure - 2 Containers used for GPR experimental study

The second set of trials was conducted using a large cubical tank (Figure 2b) with aggregate being brought to various deteriorated states using different levels of the engineered fouling mix (see Figure 3). The dimensions of the tank are 1.20m depth x 1.60m length x 0.7m to allow experimentation on a model filter drain trench that enables the extraction of a continuous radar-profile over the length of the ‘pseudo-drain’. Such an approach enabled the evaluation of the scattering response that would be harder to identify in a small container and through ‘static’ individual wiggle plots. The container was partitioned in three different sections using plywood sheets to eliminate fines migration between adjacent sections. Different aggregate – fouling compositions were evaluated throughout the study (three Sections, four fouling / water content cases) linked to deteriorated characteristics targeting condition bands defined in Table 1. Throughout the ‘pseudo-drain’ trials the following scenarios are evaluated:

- Section A; a 50cm layer of fresh aggregate placed on top a slightly fouled layer (50cm deep).
- Section B; a 50cm layer of fresh aggregate placed on top a moderately fouled layer (50cm deep) – the top layer is then subsequently fouled to moderate and high levels for follow up trials and comparisons of scattering response.
- Section C; a 50cm layer of fresh aggregate is placed on top of a ‘spent’ layer (50cm deep). The top layer is then subsequently fouled to moderate levels.

Water was then added to the tank (allowed to percolate from surface in Sections A and B) to assess the effect of moisture in the fouling-aggregate mix.

Condition Band Descriptor	Anticipated Drainage Capacity	Free Voids Ratio
Fresh Aggregate	Free Draining	> 0.7
Moderately Fouled	No noticeable drop	0.4 – 0.7
Highly Fouled	Severely reduced	0.2 – 0.4
Spent Aggregate	Practically impermeable	< 0.2

For data collection from the large-scale model drain, two central frequencies (of the same ground coupled system) were used, a 500MHz and a 1GHz antennae. In terms of data post-processing depending on the objective of each trial different filters and routines were followed. The analysis of void scattering is based on exploring and evaluating the scattering amplitude response that is used to refer back to fouling statuses as a function of amplitude attenuation. This requires the application of an amplitude envelope over the processed data to explore signal attenuation over the depth of the material in each compartment. Amplitude specific colour coding was then adopted to make radar-profiles clearer for the reader. The STFT analysis was carried out separately using Matlab.

For a typical trace and to increase clarity of information from a trial, post-processing adopted follows three steps:

- Bandpass Butterworth (adopting a range of $\left[\frac{f_c}{2}, 2 \times f_c\right]$ - where f_c denotes central antenna frequency)
- Background Removal
- Dewow

3.2 MATERIALS

The aggregate material used in this study is granite that falls within the Type B HFD specifications envelope according to British Standards (MCHW Vol. - 1 Series 500). While different fouling admixtures are expected to generate unique results in a trial, this is only evaluated in the first set of experiments using the smaller circular tank. For the analysis carried out in the smaller cylindrical container an engineered fouling material and sand fouling are adopted. For the ‘pseudo – drain’ trials, the engineered fouling mix is used to artificially ‘deteriorate’ the Type B fill and simulate on-site conditions (Stylianides et al., 2016). Material gradings for sand and engineered fouling are plotted in Figure 3 along with PSD for the Type B aggregate adopted in the study.

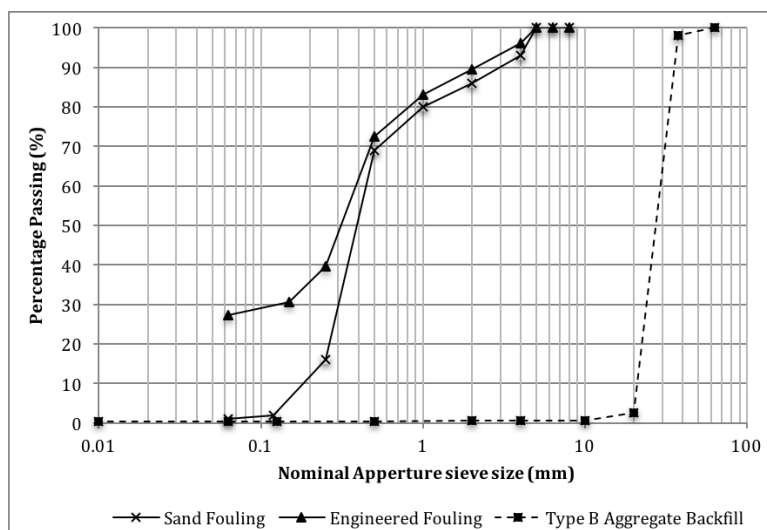


Figure - 3 Particle size distribution curves for Type B aggregate and fouling types used in study

Material mixing for the first set of trials was achieved using a vibrating table. A pneumatic drill was used to enable penetration of fouling material across the depth of the ‘pseudo drain’. In order to quantify the extent of deterioration and fouling levels in each test for a particular fouling-aggregate mix the Free voids Ratio (R_{fv}) was adopted (Stylianides et al., 2016, Stylianides et al., 2015a). The calculation of the index was thus based on the following formula:

$$R_{FV} = \frac{V_{VFRA} - V_F}{V_{VFRA}} = \frac{e_{fr}V_A \frac{M_F}{\rho_f}}{e_{fr}V_A} = \frac{e_{fr} \frac{M_A}{G_A} \frac{M_F}{\rho_f}}{e_{fr} \frac{M_A}{G_A}} \quad (9)$$

V_{VFRA} is an estimation of the volume of voids in a fresh backfill while V_F represents the volume of the fouling material. The former is calculated using e_{fr} , the void ratio for fresh Type B aggregate, adopted here to be equal to 0.65. The material’s specific gravity G_A is again extracted in the laboratory while ρ_f , defining the bulk density of the foulant, is measured to be equal to 1.5 tons/m³. This value has been derived using the engineered fouling material used in this study and a number of compaction tests.

3.3 RESULTS

3.3.1 EVALUATION OF ELECTRICAL PROPERTIES OF AGGREGATE MIX

Figure 6 represents how propagation velocities assessed from (static) traces change for different fouling levels as extracted from the cylindrical tank analysis. Looking at the radargrams presented in Figure 4, it is rather trivial to identify the surface reflection at the uppermost of the circular tank, and interface between the aggregate and steel plate and the bottom-end of the container. It is also clear that samples of higher fouling concentrations give rise to higher dielectric constants (larger measured two-way travel times and thus lower propagation velocities).

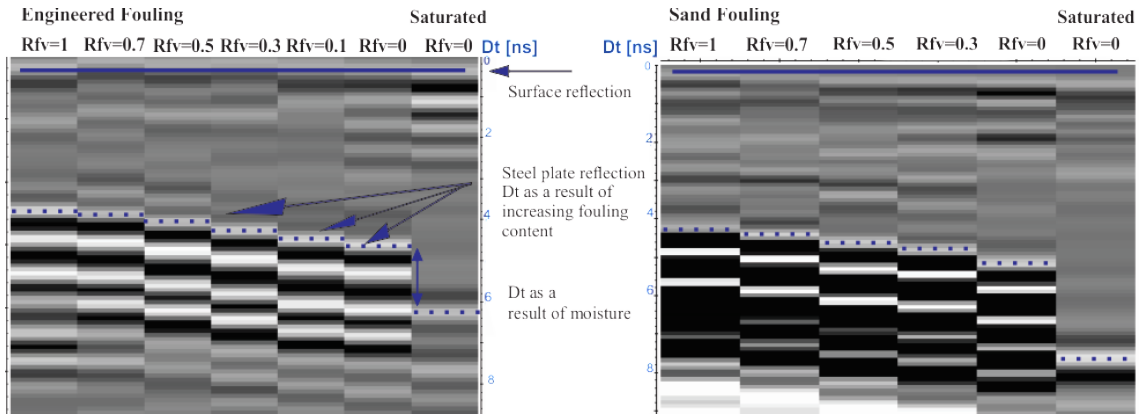


Figure - 4 GPR response from circular container for increasing fouling levels using engineered and sand fouling

The range of ϵ_r values as the aggregate condition moves from ‘fresh’ to ‘spent’ varies according to fouling type used. The permittivity values are calculated by measuring the two way travel time (by identifying reflections from air-aggregate and aggregate basal-steel plate interfaces) within a medium of known depth (360mm). ϵ_r for fresh aggregate is calculated to be equal to 3.06; using the engineered fouling $\epsilon_{r,spent} - \epsilon_{r,fresh} = 1.6$. For sand fouling, the range of dielectric constants between the two condition extremes

is calculated to be smaller, $\epsilon_{r,spent} - \epsilon_{r,fresh} = 1.2$

Condition Descriptor	ϵ_r	
	Engineered Fouling	Sand Fouling
Fresh Aggregate Dry	3	
Fresh Aggregate Wet	4	
Spent Dry	>4.6	>4.2
Spent Wet	8.8	8.5

A clearer deviation of the electrical property of the aggregate-fouling mix is apparent when water is introduced in trials. The dielectric constant is visibly more sensitive to water rather than increasing fouling levels. These observations are in line with most ballast studies (presented in previous sections) and are visualised qualitatively in the profiles presented in Figure 4. Using the engineered fouling, the two way travel time for a wet spent sample ($\Delta t'$) between the surface of the material and the steel plate is shown to increase by ~1.5 times in comparison to the two way travel time for a dry spent sample (Δt). Assuming u represents the wave propagation velocity in a dry spent state and u' the one in a wet spent state, $\Delta t' = 1.5 \times \Delta t$ and $u' = \frac{u}{1.5}$. Using equations (3) and (5), $\epsilon_r' = \left(\frac{c}{u'}\right)^2$ thus the anticipated dielectric constant for a wet spent sample (ϵ_r') is estimated to be $1.5^2 = 2.25$ times larger than the same parameter for a dry spent sample (ϵ_r).

3.3.2 VOID SCATTERING

The scattering evaluation from within the large container follows the same principles as set by Al-Qadi et al. (2005). The increasing fouling levels produce reduced scattering and this is visible in raw data. A comparison of the response picked up from 500MHz and 1GHz antennae can be seen in Figure 5. While there can be merit in using the lower end of available central frequencies in a condition survey (easier perhaps to identify boundaries), localised scattering is not noticeable thus making the condition assessment task challenging. Amplitude peaks in the lower sections of the higher frequency radargram (bottom right corner of the figure) are reduced. This correlates well with the increasing fouling levels in that part of 'pseudo-drain' hence suggesting increased fouling levels can be identified by visual queues in radargrams.

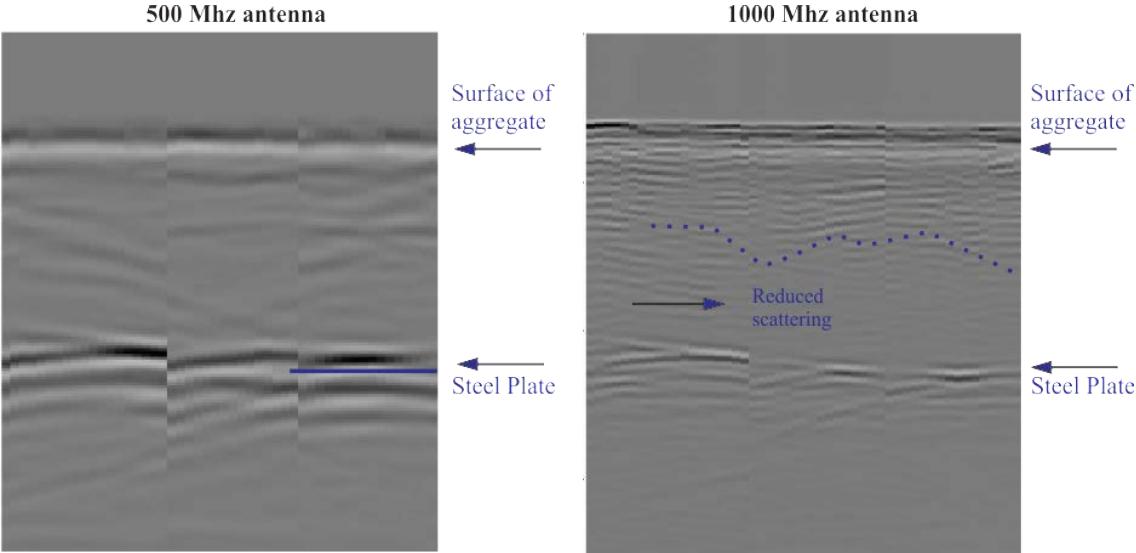


Figure - 5 Radargrams of 500 Mhz antenna (on the left) and 1000Mhz antenna from identically fouled sections; drop in scattering intensity can be noticed in bottom right corner of 1000Mhz radagram that correlates to the highly fouled sections

A representation of the scattering amplitude concept in the designed medium for an incident wave that travels through a fresh aggregate to a section that is spent can be seen Figure 6. The intensity of the envelope applied on the A-scans is smaller once the wave enters the highly fouled section. The large peak at the bottom end of the plot is a result of the steel plate producing high reflections. The amplitude reduction from extracted traces can hence be correlated to increasing fouling levels assuming that the total energy attenuation can be attributed to deteriorating sections.

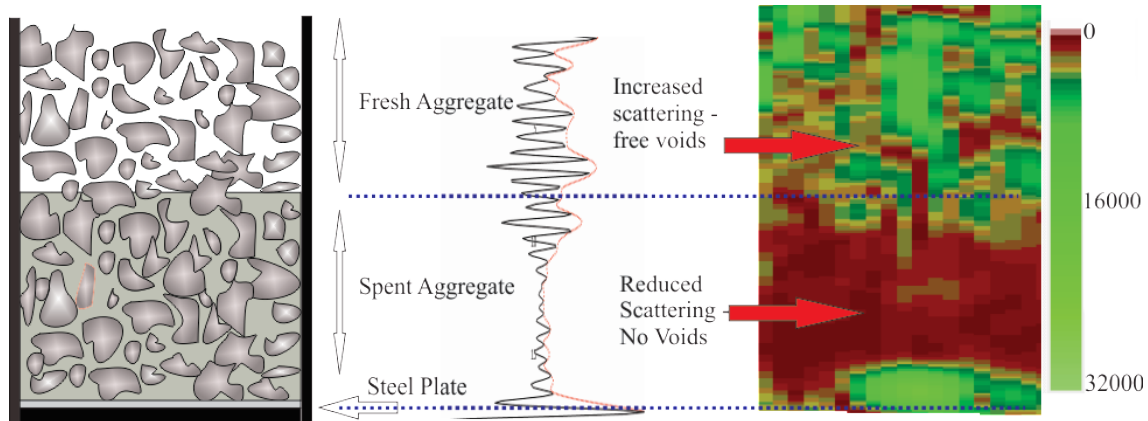


Figure - 6 Scattering response for a wave travelling through fresh aggregate to a spent section.

By applying the envelope on the extracted traces (1 per mm across the length of the cubical container) the three (dry) scenarios (cases A to C) that match in-situ fouling conditions are evaluated in context (Figure 7). Fresh or relatively clean sections produce significant scattering; large amplitude peaks are apparent for EM traces traveling through sections with $R_{fv} > 0.5$. This can be observed in all uppermost layers in Case A throughout all three sections of the pseudo-trench. The increasing fouling levels in sections B,C in Case B (R_{fv} moves from 1 to 0.5 for uppermost layers of Section B and from 1 to 0.6 for uppermost layers of Section C) have an impact on the EM wave and increased attenuation is observed albeit scattering events are still noticeable. By further increasing fouling levels in section B for the last dry set of evaluated fouling conditions (R_{fv} for uppermost layer now 0) a further reduction in the applied amplitude envelope is noticeable. Throughout the three cases (A to C) the fouling composition of section A remains unchanged providing a baseline reading for the trial. As anticipated the scattering events throughout the dry cases for this particular section remain steady.

When water is introduced in the box (allowed to percolate through the fill from the top) in Case D, the wave's velocity is expected to decrease (so two way travel times increase) and the amplitude peaks in the saturated aggregate/fouling parts diminish. Looking at Figure 7, the lowest radagram set (Case D) presents the case of two wet sections that in previous cases would be presented with a significant scattering indicative of available void space. In the wet sections trial, scattering is weakened (almost impossible to notice) and the basal steel plate reflections are hardly identified (more apparent in Section B that combines low R_{fv} and high water content)

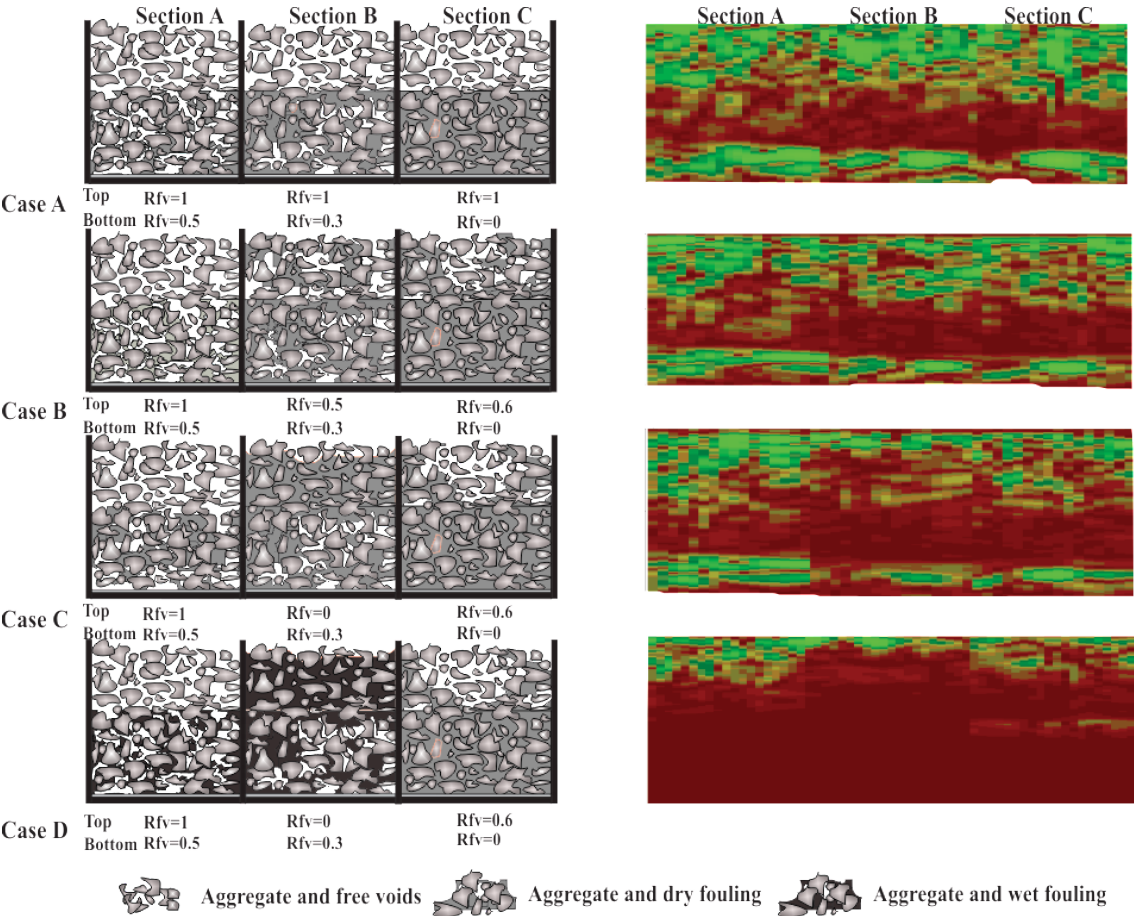


Figure - 7 Comparison of scattering response from various fouling conditions adopting scattering amplitude plot used in Figure 6

3.3.3 TIME FREQUENCY ANALYSIS

A-scans from the three sections for a dry (Case C) and a wet trial (Case D) are selected, exported and processed in MatLab; these represent sections with identical fouling levels. STFT spectra are presented in Figure 8.

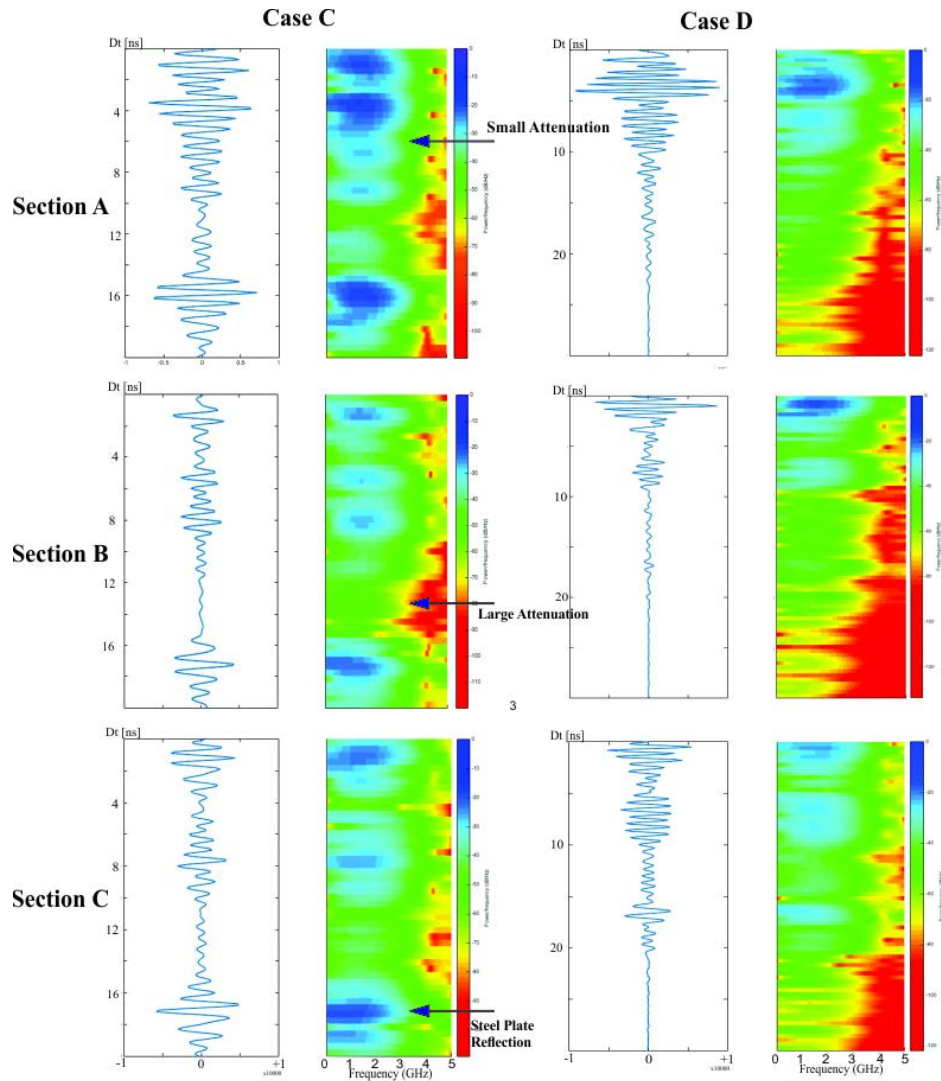


Figure - 8 Comparison of STFT spectrum for different A-scans extracted from (dry) Case C and (wet) D; higher energy dissipation for wet trials is obvious from plots

In line with the analysis from voids, the signal's energy can be seen to attenuate with increasing fouling levels. The power dissipation in the medium can be used to reach conclusions for the location of fouled sections and of the basal plate reflector (or of any other distinctive boundary). Looking into Case C and Section A, the large void space of the top 50cm of material produces no significant energy drop; when the EM wave enters the moderately fouled aggregate ($R_{fv} = 0.5$) at the lower part of the same section, some energy gets lost and this can be seen in the extracted spectrogram. Sections B and C have similar responses with the latter case presenting a smaller level of attenuation at the uppermost layers matching the higher available void space to begin with. In Trial D (wet, Case D in Figure 7), Sections A and B exhibit much bigger energy attenuation than the previous set of spectrograms; this is attributed to the conductive nature of the water added in the pseudo trench that gives rise to higher rates of attenuation of the signal as it travels through the fouled material

4 CONCLUSIONS

The GPR can potentially offer an effective and relatively fast assessment technique to collect and evaluate condition and deterioration information of in service HFDs. The paper has presented pavement and ballast evaluation thinking originating from the various forms of data processing options available to GPR users in an effort to identify the prerequisites for HFD non-destructive evaluation. The work presented (both in terms of analysis of state of the art and experimental trials) focuses on the practical side of geophysical investigations and describes a methodological solution to the ongoing issue of absence of HFD assessment techniques.

With no formal framework established yet to break-down GPR data collection and processing requirements for HFDs, the exploratory study of railway and pavement asset assessment techniques (focusing on applicability and extent of industrial adoption) leads to the laboratory based assessment of artificially fouled type B aggregate backfill. The data collection and processing methodologies used aim to establish a baseline for in-situ HFD condition data collection and techniques based on void scattering and frequency analysis are thus presented. Such approaches are perhaps clearer and more comprehensive to a railway engineer but while HFDs are clearly a highways drainage solution (and a quite popular indeed), design characteristics and deterioration modes tend to follow railway ballast principles. The extensive exploratory review of academic and industrial practise communicates how pavement thinking might not necessarily offer all the relevant tools required to 'do the right job and the job right' and a pragmatic way forward is hence proposed.

The dielectric calibration study defined a range of dielectric constant values pertaining to different condition states of type B HFD backfill. The impact of moisture and of the combined 'footprint' of water and fouling is identified and hence the requirement to integrate GPR data processing with sample extraction and moisture / fouling specific 'tuning' exercises. ϵ_r for the backfill is calculated to range between 3 and 8.8 as a function of R_{FV} and water content with results being more sensitive to moisture rather than fouling materials. It is thus evident that making typical assumptions of dielectric constants and employing them on site may fail to paint the full picture for in-service drains without combining the GPR with semi-destructive sampling and sorting.

The pseudo-trench trials adopting either the analysis from void scattering or frequency analysis were aligned to the condition descriptor used in the study (Free Voids Ratio) showing a good correlation of available void space and GPR output. The two antennae adopted (500MhZ and 1GhZ) exhibit a range of results. The lower frequency option (that in principle offers higher penetration capabilities) fails to capture scattering information from the evaluated fouling cases but can potentially be used to identify unique layers deeper in an in-situ trench. The adoption of such a system thus cannot be expected to offer significant value in terms of in-situ studies and should be avoided or combined with a higher frequency unit to only offer supplementary condition information.

The approach based on fitting an amplitude envelope shows a lot of potential as a good correlation of fouling levels and intensity of scattering events has been achieved. The effect of water percolating through the aggregate can be observed in Case D with scattering events diminishing and increased energy attenuation through the aggregate fill. The results are interpreted here in a qualitative manner. Information regarding fouling is linked to the

‘scattering intensity’ colour map produced for this particular trial within ReflexW (see Figure 7). A geophysicist can extract condition information for the aggregate fill by developing suitable colour maps once the extracted amplitude envelopes for fresh (clean), moderately fouled and spent sections are studied and attenuation levels are extrapolated to the extremes.

Similar conclusions are reached using the combination of time and frequency domains. The use of frequency spectra though comes with limitations; one trace can be extracted per STFT analysis and a large number of traces have to be processed for a linear asset that spans many kilometres in a road network. While the STFT routine can be in principle employed, the fact that the data handling should be completed in a programming language like (or similar to) Matlab may limit rolling out such an approach in the industry at the time being. The frequency domain is still though an area for future academic research.

Considering the lack of any detailed assessment strategy to date, this paper aims to communicate the need to establish standard deterioration recognition patterns linked to HFDs using a non-destructive technology. Raw data collected from in service trenches may be challenging to process due to their complicated form (HFDs are not structures designed with superimposed layers that will present electrical property variations giving rise to reflections). The adoption of specific central antenna frequencies and of a particular processing routine can though enable in-situ, non-destructive HFD surveys. Supplemented by dielectric constant libraries linked to condition classes and localised sieving/sorting data, asset condition information can be collected and used for maintenance planning and prioritisation

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