Value Analysis: Better Asset Management

Final Report

7 December 2017

The National Infrastructure Commission

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Executive summary

Purpose of study

The purpose of this study is to assess, on behalf of the National Infrastructure Commission (NIC), the potential value and expected benefits of investing in new digital and data-driven technologies to support better asset management and drive positive outcomes across infrastructure sectors.

We have undertaken Cost Benefit Analysis in the rail and water sectors across a selection of smart monitoring case studies and have applied the results of this analysis to the wider rail and water networks to understand the potential benefit of investing in this technology.

Key results

In our central case scenarios:

- Targeted implementation of existing technology could generate benefits of at least £3 for every £1 of cost on the rail network.
- Targeted implementation of existing technology could generate over £2 of benefits for every £1 of cost in the water sector.
- Smart monitoring could reduce the economic cost of asset failures on the rail network by £600M a year.

Under some scenarios these returns could be even greater. For example, with significant (but feasible) reductions in the cost of technology:

- Rollout of smart metering in the water sector could generate lifetime cost savings of £600M to £1.5bn.
- Rollout of permanent acoustic logging to enable rapid identification and location of water leaks could generate lifetime cost savings of £100M.

Behind these headline numbers, our report sets out a number of supporting conclusions:

Smart monitoring can deliver significant returns on investment, particularly when targeted carefully

Even basic monitoring technology could generate substantial returns if targeted in the right areas.

For example, technology to reduce the impact of rail bridges being struck by road vehicles should be targeted at those bridges most at risk of being struck and with the highest levels of rail traffic.

In the water sector, technology that reduces water consumption or allows for quick identification of leaks will deliver the best return for those water companies with the highest marginal cost of supply. These are typically in water stressed regions.

Reducing the level and impact of asset failure is a key priority

This is particularly the case for the rail sector, where disruption to services results in wasted time for passengers and dissuades the people affected from travelling in the future.

We estimate that monitoring technology to reduce the level and impact of asset failures could reduce the financial and economic cost of rail disruptions by around £600M per year.

The installation of similar technologies on the UK light rail network, and in particular London Underground, is likely to generate substantial further benefits.

For some technologies and assets the returns are potentially huge, but currently unproven

The impacts of major rail asset failures, such as the collapse of a viaduct or a retaining wall, can extend to tens or even hundreds of millions of pounds per incident. The use of monitoring technology to provide early warning of these total asset failures could deliver a substantial potential financial and economic prize. There are also potentially significant safety benefits from removing or reducing the need for human inspections.

These financial, economic and safety benefits apply across all transport sectors. There are few current trials of this monitoring technology application and therefore we see benefit in investment in pilot studies to establish the value in this context.

There is a similar role for monitoring technology in the water sector to avoid critical asset failure such as trunk main bursts, which can cause significant disruption to communities and transport networks.

The appropriate scale of a financially viable technology rollout will depend on future cost reductions

The newer and more innovative applications of monitoring technology are currently expensive, as they are typically small-scale interventions in the form of research projects or pilot studies.

For example, trials of technology to monitor the structural health of rail bridges have had installation costs of tens of thousands of pounds per bridge. The installation cost of smart metering for water is currently over £300 per property.

As with all new technology, it is reasonable to expect the cost of the equipment to reduce significantly in the future. Parallel developments such as the Internet of Things and cloud computing will reduce the cost of collecting, storing and analysing data from the monitoring equipment.

These cost reductions would increase the returns on investment and extend the range of implementations that would be economically worthwhile.

There are challenges to realising the full benefits of smart monitoring

Even where there is a strong economic case to invest in smart monitoring technology, the financial return for infrastructure companies may be weak, particularly when considered within the limits of existing five-year regulatory cycles.

Additional incentives may be required to maximise take-up. This could be in the form of ‘pump priming’ funding, or regulatory incentives for early adopters.

Asset managers are not always incentivised to collaborate with other organisations or to share information and innovations, particularly in a competitive environment. This is a barrier to understanding the full potential of data-driven technologies and to achieving cost reductions through better market knowledge and the economies of scale possible from mass adoption.

There are wider opportunities from smart infrastructure

This study has focused on a limited number of specific technology case studies, and a comparison of our results with the wider portfolio of evidence.

The largest benefits are likely to be obtained from combining data from multiple monitoring technologies, enabled by investments to improve asset information, data management and other components of smart infrastructure systems such as decision support tools and prescriptive analytics. Equally important are changes to asset management and operational procedures to ensure maximum value is derived from the available information.

The greatest unquantified opportunity is from the value of information being shared across multiple sectors, improving productivity across infrastructure and construction as part of a ‘system of systems’ National Digital Twin. This could deliver efficiencies at strategic, tactical, and operational levels through improved coordination between different infrastructure owners, as well as wider value from the availability of open data sources to deliver better public services.

Case studies investigated

Table 1 provides a summary of the cases studies we have investigated.

Table 1: Case studies investigated

Case study	Principal monetizable benefits	Other potential benefits	Financial return	Financial + economic return
Marsh Lane Rail Viaduct	Time savings Increased rail fares revenue Reduced rail-road modal transfer	Avoidance of major asset failure (although not the key application in this study) Maintenance cost savings	Low due to small impact of mitigated speed restriction. Few speed restrictions through structures defects exist on the network. Other benefits have not been quantified due to a lack of information.	Low due to small impact of mitigated speed restriction. Few speed restrictions through structures defects exist on the network. Other benefits have not been quantified due to a lack of information.
Rail bridge renewals	Deferred renewals costs	Avoidance of major asset failure (although not the key application in this study)	Low, but could be improved substantially through reduction in technology costs	Low, but could be improved substantially through reduction in technology costs
Rail bridge strikes: CCTV based monitoring	Time savings Increased rail fares revenue Reduced rail-road modal transfer Reduced inspection costs	Potentially improved workforce safety through fewer inspections	Strong for high and medium frequency struck bridges, although not our recommended technology solution. Case improved when most valuable routes targeted.	Strong for high and medium frequency struck bridges, although not our recommended technology solution. Case improved when most valuable routes targeted.
Rail bridge strikes: highway warning system	Time savings Increased rail fares revenue Reduced rail-road modal transfer Reduced inspection costs Reduced bridge/track repair costs Reduced road haulier/customer costs Improved safety	Transfer of traffic data to the highway authority, for planning purposes	Strong for high and medium frequency struck bridges. Case improved when most valuable routes targeted.	Strong for high and medium frequency struck bridges. Case improved when most valuable routes targeted.
Rail bridge strikes: autonomous vehicle control		Transfer of traffic data to the highway authority, for planning purposes	Strong for high and medium frequency struck bridges. Case improved when most valuable routes targeted.	Strong for high and medium frequency struck bridges. Case improved when most valuable routes targeted. Potentially strong for lower frequency struck bridges, depending on potential cost savings.
Smart water meters	Reduced meter reading costs Deferred water investment cost Deferred wastewater investment cost Reduced hot water consumption Reduced insurance premiums	Improved targeting of asset renewal investment, allocative efficiency and network optimisation. Improved customer experience from reduced bill uncertainty, potential social care monitoring application.	Low, but analysis excludes regulatory mechanisms linked to company performance such as leakage	Low for most companies using current technology supplier costs. Strong for companies in water-stressed regions with potential future reductions in technology cost.
Permanent acoustic logging of water distribution network	Reduced operational costs from more efficient targeting of leakage detection Reduced cost of leak repairs and economic impact from earlier detection	Improved targeting of asset renewal investment to reduce leakage. Reduced interruptions to supply	Highly sensitive to company's active leakage control budget, strong return on investment for companies with highest current spend.	Comparable to financial return – operational cost savings dominate

1 Project Definition

1.1 Background

Mott MacDonald has been commissioned by the National Infrastructure Commission (NIC) to examine how new (smart) technologies can support better asset management and whether a compelling business case can be developed for expanding the use of these technologies.

The requirement for this study has arisen from the Autumn Statement 2016, in which the Chancellor of the Exchequer requested that the NIC:

- Identify which emerging technologies have the most potential to optimise existing and future infrastructure management, performance, and maintenance, to support economic growth.
- Make recommendations to government on what actions should be considered to support smart technology deployment across infrastructure areas and sectors.

Evidence gathered by the NIC, including through this study, will be used to inform policy recommendations.

1.2 Objectives

The main objective of the study is to demonstrate the value and expected benefits of investing in new technologies to support better asset management and drive positive outcomes across infrastructure sectors.

The study is informed by a cost benefit analysis (CBA) in line with the principles set out in the HM Treasury Green Book (Appraisal and Evaluation in Central Government).

1.3 Scope and Desired Outcomes

The NIC has decided to demonstrate the value and expected benefits of investing in new technologies by focusing on two sectors, rail and water asset management. The study therefore has two key parts:

- **Part A – Structural rail assets**: Examining monitoring technologies for structural rail assets, to support improved maintenance processes, reduced disruption, and other benefits.
- **Part B – Water sector**: Examining monitoring technologies in the water sector, to support better asset management and increased efficiencies.

Key findings from Part A and Part B have been developed into a set of recommendations and relevant conclusions that can be applied to other infrastructure sectors. This wider extrapolation forms Part C of the study.

1.4 Study limitations

This has been an eight-week study from project inception to submission of this final report. This has limited the amount of data we have been able to acquire and analyse. In turn this has limited the number of different technologies we have been able to consider. In section 5 we have set out areas where further work would be required to extend the evidence base for our conclusions.

To expedite data acquisition, we have contacted, both formally through NIC, and informally through our own network, key individuals within the rail and water industries. We are grateful, in particular, for the support of Network Rail, the Cambridge University Centre for Smart Infrastructure and Construction (CSIC), Anglian Water, Affinity Water, SES Water, Southern Water, Thames Water, Yorkshire Water, United Utilities and Water UK.

Given the short project timescales, the analysis undertaken was necessarily high-level. The figures shown in this report are therefore generally intended to be indicative orders of magnitude, rather than precise estimates.

We have discussed our assumptions with stakeholders, such as Network Rail, and participating Water Companies, however these assumptions are Mott MacDonald figures unless stated.

The original scope of work for the rail sector (Part A) was to scrutinise evidence from a case study provided by CSIC, to produce a cost benefit analysis using this evidence and to extrapolate it to the wider rail network. Having discussed the case study with CSIC, it was clear that the monitoring installation at Marsh Lane was not intended to be a prototype installation to be implemented across the rail network, but was instead a research project to understand the dynamics of masonry viaduct response. As a result, it would be extremely difficult to extrapolate the evidence from this project to evaluate economic benefit across the network. We therefore agreed with NIC to broaden the scope of the study to consider a wider body of evidence applicable to a greater proportion of GB rail structures.

1.5 Report structure

The remainder of this report is structured as follows:

- Section 2 presents our rail sector analysis
- Section 3 presents our water sector analysis
- Section 4 presents a summary of how our findings could apply in other infrastructure sectors
- Section 5 presents our key conclusions and recommendations
- Appendix A presents our long list of water case studies
- Appendix B presents benefits maps for our short list of case studies
- Appendix C presents the list of rail structures asset restrictions for the GB Network
- Appendix D provides a list of study references
- Appendix E summarises our Cost Benefit Analysis Methodology
- Appendix F provides a list of stakeholders who attended water and rail sector workshops
- Appendix G provides a synopsis of the power networks asset base and market

1.6 Abbreviations used in the report

AIC – Annual Incremental Cost

ALC – Active Leakage Control

AMI – Advanced Metering Infrastructure

AMP – Asset Management Plan

AMR – Automated Meter Reading

BCR – Benefit to Cost Ratio

CBA – Cost Benefit Analysis

CP5 – Network Rail Regulated Control Period 5 (2014-2019)

CP6 – Network Rail Regulated Control Period 6 (2019-2024)

CSIC – Cambridge University Centre for Smart Infrastructure and Construction

CSPL – Customer Supply Pipe Leakage

DfT – Department for Transport

FTE – Full-Time Equivalent

FWI – Fatalities and Weighted Injuries

GIS – Geographic Information System

GPRS – General Packet Radio Service (a telecommunications standard)

GPS – Global Positioning System

IT – Information Technology

IoT – Internet of Things

LITSoN – Linking Innovation to Societal Needs

LTE-M – Long-Term Evolution Category M (a telecommunications standard)

NB-IoT – Narrow Band Internet of Things (a telecommunications standard)

NIC – National Infrastructure Commission

NPV – Net Present Value

O&M – Operation & Maintenance

Ofgem – Office of Gas and Electricity Markets

Ofwat – Water Services Regulation Authority

ONS – Office for National Statistics

PCC – Per Capita Consumption

PFPI – Abbreviation for the cost of delays to rail services, viewed as proxy for the loss of fares revenue

PR14 – Ofwat's 2014 price review for UK water companies

R&D – Research & Development

RSSB – Rail Safety and Standards Board

SELL – Sustainable Economic Level of Leakage

SMIS – Safety Management Intelligence System

SMS – Short Message Service

Totex – Total expenditure

WebTAG - Department for Transport Appraisal Guidance

WRMP14 – Water Resources Management Plan 2014

WRMP19 – Water Resources Management Plan 2019

WTP – Willingness to Pay

2 Rail Sector Analysis

2.1 Introduction

Our original scope of work was to assess the evidence from a single pilot installation of monitoring technologies on a masonry arch viaduct at Marsh Lane in Leeds, to produce a Cost Benefit Analysis (CBA), and with the evidence from this case study, to seek to extrapolate the results of this analysis to the wider rail network.

The Marsh Lane pilot study is being undertaken by CSIC in partnership with Network Rail, and was set up as a research project with the objective being to better understand the dynamic response of this viaduct to rail traffic and identify the mechanisms that drive its degradation.

Having discussed this case study with CSIC and Network Rail, we felt it would be beneficial to add further case studies to our scope of work, exploring other applications of technology to monitor rail structures. We anticipated that this would enable us to draw wider conclusions about the benefits of monitoring technologies in the rail sector. To this end we have also looked at the potential of technology to reduce the impact of bridge strikes by road vehicles, and to defer the replacement and renewal of existing rail bridges.

2.2 Summary of current rail structures assets

2.2.1 Current practice

At present, Network Rail's management of the risk of failure of rail structures is based on monitoring their current condition and identifying changes in condition, using information from periodic visual and tactile (touching) examinations. For certain structure types such as bridges, condition data is supplemented by validating the structures ability to withstand applied loads. The use of instrumented monitoring systems, which involve the installation of sensors to gather numerical data in a similar way to the system employed by CSIC at Marsh Lane viaduct, is not widespread. Rather it is used very selectively for specific purposes on a limited number of structures, for example to gain a detailed understanding of structural behaviour to support assessment and justify an increase in load capacity, or to monitor the progress of deterioration and control risks associated with the temporary deferral of planned remedial works.

2.2.2 Number and value of rail structures

To understand the relative size and make-up of the potential prize that may be unlocked through the use of smart monitoring, it is important to understand the particular attributes of each asset type. These include the typical asset life, asset replacement costs, annual renewal and maintenance spend, and impact of asset failures (for example, in terms of safety risk and operational disruption).

Table 2 shows the number and total replacement cost of structures assets on the GB national rail network. There are currently almost 72,000 structures in total of which nearly 28,000 are bridges. Sixty percent of bridge assets carry the railway over a road. The total asset value of all structures is estimated at £251bn, of which bridges account for almost two thirds.

The total cost of structures renewals in 2015/16 is estimated by Network Rail at £405M, equivalent to 15% of the total asset renewals expenditure by Network Rail during that year. Total maintenance costs are not separately reported for structures. However, the cost of structures inspections in 2015/16 is understood to be circa £80M, and the overall maintenance spend for Civil Assets (which includes rail structures and earthworks) was £184M.

Based upon figures provided by Network Rail[1], loss of rail fares revenue associated with the failure of all structures assets for 2016/17 is circa £20M per annum, with most of this figure (£12.3M) relating to 'bridge strikes' (where a road vehicle hits a railway bridge). The £20M figure represents around 5% of the £350M - £500M total annual loss of rail fares revenue to asset problems.

Table 2: 2015/16 Rail structures assets by quantity and asset value

Asset Type	Quantity	Replacement Cost
Bridges	27,800	£162bn
Footbridges	1,412	£4bn
Culverts	21,649	£10bn
Tunnels	627	£26bn
Retaining Walls	19,915	£43bn
Coastal/Estuarine Defence	473	£6bn
Total (Rail Structures)	71,876	£251bn

Source: Network Rail[2]

2.2.3 Rail Structure Related Safety Risk

Safety incidents across the UK rail industry are recorded in a Rail Safety and Standards Board (RSSB) maintained national rail safety database called the Safety Management Intelligence System (or SMIS). RSSB also maintains a Safety Risk Model (which identifies frequency rates and safety risk for a list of rail related hazards) for use by the industry.

No overall safety risk value is given for a particular asset group. However, based upon a review of the 3,000+ entries included in the Safety Risk Model (v8.1) it is estimated that the safety risk associated with rail structures is of the order of 24 Fatalities and Weighted Injuries[3] (FWI) per year. It should be noted however that the majority (over 95%) of this risk is human behaviour related (such as suicide, trespass, slips, trips and falls), rather than structural related (such as structure or component failure). The relatively low level of structural failure safety risk means that there is limited opportunity for structural health monitoring (say) to have a significant impact upon *global* rail safety risk. That said, monitoring has and will continue to be a valuable asset management tool to safely manage particularly degraded or high-risk assets, and the ongoing development of new 'smart technologies' for monitoring and risk evaluation are likely to bring significant opportunities in this area over time.

[1] Network Rail PFPI costs for 2012/13 – 2016/17, In this report, compensation payments under Schedule 8 of the track access agreements between Network Rail and train operators are used as proxy for loss of fares revenue

[2] Network Rail Civil Asset Register and electronic Reporting System (CARRS) data (October 2017) and Network Rail Regulatory Financial Statement to year end 31/03/2017

[3] Non-fatal injuries are given an equivalent fatality weighting to facilitate risk assessment (e.g. 10 major injuries to 1 fatality etc)

2.3 Case study analysis

2.3.1 The Marsh Lane Viaduct Case Study

2.3.1.1 Background

Marsh Lane Viaduct is in Leeds on the London and North Eastern (LNE) route and is of masonry arch construction, dating from the expansion of the railways in the Victorian era. CSIC was engaged by Network Rail to monitor the viaduct as a field experiment in the potential use of new monitoring technologies to *"better understand the dynamic response of the viaduct to rail traffic and identify mechanisms that drive the degradation"*[4]. The structure was described as being *"visibly damaged due to water leakage and past settlements"* which had resulted in Network Rail imposing a speed restriction on trains passing over it. Several maintenance interventions had been implemented over the last fifteen years, but these had not prevented further deterioration.

CSIC set out a programme of monitoring using new and emerging technologies that are at a deployable level, and had been used elsewhere for specific purposes, but were yet to find widespread use in the transportation infrastructure sector for structural monitoring purposes.

The technologies included the installation of fibre optic sensors to make dynamic distributed strain measurements, videogrammetry to make dynamic displacement measurements, and laser scanning to accurately measure the shape of the structure and quantify any changes over time. Upon completion of the exercise, CSIC concluded that their analysis of the data from the fibre optic sensing system had provided "*a new understanding of how the arches of the viaduct interact during dynamic rail loading"*, and that the project had "*delivered a better understanding of the structural response of masonry viaducts"* (i.e. implying an improvement in the general understanding of the behaviour of this type of structure under rail loading, potentially applicable to other similar structures). Also, that the study:

- provided *'an opportunity to modify Network Rail's response to emerging issues, reducing delays and negative effects of passenger experience'*, and
- *'allowed CSIC to … better evaluate the effectiveness of potential intervention techniques'.*

2.3.1.2 Appraisal

We have investigated the potential financial and economic benefits of this particular case study.

One benefit relates to the removal of Temporary Speed Restrictions (TSRs). In the case of Marsh Lane, monitoring enabled the TSR to be relaxed, but did not result in a monetary benefit as the restriction was on a low speed route section and the resultant improvement in journey times was very small.

We have analysed Network Rail delay data[5] and delay cost data[6], to understand the potential to mitigate long-standing TSRs on bridges, in particular where the speed restriction is much greater. The data indicated that annually, only a small number of structures have TSRs lasting more than three months (which was assumed to be the minimum time to design and install a monitoring system and have enough data to warrant changing any speed restriction).

[4] Italicised references refer to Cambridge Centre of Smart Infrastructure and Construction (CSIC) 2017 Annual Report
[5] Network Rail Train Delay data (2014/15 to 2017/18 Period 7)
[6] Network Rail PFPI costs for 2012/13 – 2016/17

We were unable to acquire data on Permanent Speed Restrictions (PSRs), however, we consider that the business case may be better than the case for TSRs given the long standing nature of these restrictions. This value would relate to improvements in journey times and/or operational resilience.

Another potential benefit is that the understanding of structural behaviour monitoring could prevent the need for certain maintenance interventions. The equipment at Marsh Lane was not installed in time to achieve this, however, this may not be the case elsewhere.

Indeed, this case study highlights the opportunity that better asset knowledge gained through new monitoring technologies can support improved decision making and cost-effective maintenance. With the understanding of structural behaviour that the system provided, the previous maintenance intervention might have been more focused and potentially lower cost. Additionally, if monitoring had been in place before and after the intervention, the monitoring could have quantified the effectiveness of the intervention, and if monitored long term, the intervention's durability.

Monitoring, such as that installed at Marsh Lane Bridge, together with structural modelling and analysis, can provide improved understanding of the behaviour of structures under dynamic loads. This improved understanding can support an evidenced based approach to setting appropriate operational restrictions on the structure (such as temporary or permanent speed restrictions), with associated improved safety and/or reduced service disruption benefits.

Data from further trial applications of new monitoring technologies that build upon the lessons from the Marsh Lane study would be required to confidently evaluate the potential costs and benefits of wider rollout of these technologies for rail structures.

The monitoring costs associated with the Marsh Lane study were reported to be in the region of £40k (for planning, installation and equipment, but excluding structural and data analysis inputs). These costs relate to research and early technology trials, which would be unlikely to reflect the (reduced) future cost of an optimised and targeted sensing system.

With limitations on the available data as discussed above, a monetised CBA based upon extrapolating the data from this particular case study was not possible.

2.3.1.3 Other potential benefits

One potential application of technology similar to that deployed by CSIC at Marsh Lane is to provide advanced warning of infrequent but highly disruptive structural asset failures. The financial and economic costs of major structure-related incidents such as the collapse of Stewarton rail bridge (in 2009), and the collapse of the sea wall at Dawlish Warren (in 2014) can extend into the tens or hundreds of million pounds per event.

It is important to distinguish between two categories of major failure:

- The first is where failure is the consequence of an event or load that the structure was not designed for, such as an exceptional weather or flood event. A structural health monitoring system has the potential to provide advance warning of those assets most at risk by recording their response to lesser events that do not result in failure. For example, monitoring the creation of scour holes at bridges founded in rivers under 'normal' storm conditions, can provide clues as to the potential risk of scour under an 'extreme' storm or flood event. Better predictions should facilitate cost-effective mitigation (e.g. targeted underpinning of those bridge foundations considered to be at greatest risk). Even if a failure is not prevented, this type of system could provide rapid warning that the failure is occurring or has occurred, allowing emergency risk management measures to be put in place to limit the consequences.

- The second category is where failure results from a more gradual asset degradation that cannot reliably be detected by visual inspections, but is potentially detectable using new monitoring technologies. The bridge collapse at Stewarton is a good example of this, where buried elements of the bridge girders had experienced undetected and severe corrosion.

Additionally, the use of new monitoring technologies could result in safety and possibly also cost savings in situations where they provide a means of reducing or eliminating the need to expose humans to hazardous situations, for example in the course of undertaking underwater bridge foundation inspections by diving or the inspection of high-level bridge elements using roped access techniques.

Appendix C provides a list of safety-related incidents on rail structures which could potentially be avoided or mitigated by the use of new and emerging monitoring technologies.

Greater use of these technologies for structural health monitoring could potentially generate significant value, as and when:

- The capabilities of new technology develop;
- related knowledge and experience in the industry increases; and
- the associated costs reduce.

This is especially likely when installed selectively on higher-risk and critical assets. To this end, experience and data from further trials and studies of the type undertaken at Marsh Lane viaduct will be necessary and it is recommended that a separate, more detailed and wide-ranging study be undertaken to more confidently establish a business case for technologies and scenarios with the greatest potential.

2.3.2 Bridge renewals case study

2.3.2.1 Background

The key CBA assumptions for this example are shown in Table 8 (Appendix section E.3.)

Bridge renewal covers both bridge replacement (new for old) and bridge strengthening and refurbishment. A breakdown of Network Rail renewal expenditure for Rail Structures for 2016/17 is provided in Table 3.

Table 3: Renewals Expenditure on Rail Structures, 2016/17

Asset Group	Expenditure, £M
Rail over road or rail bridges	£252
Road over rail bridges	£60
Major Structures	£21
Tunnels	£21
Other Structures	£51
Total	£405

Source: Network Rail Regulatory Financial Statement to year end 31/03/2017, Statement 9b

Apart from where renewals are required due to an urgent need (e.g. following a structural collapse), a considerable amount of structural analysis work and feasibility design study will typically be undertaken in advance of the decision to expend limited financial resources on a renewal scheme. Monitoring is sometimes used (especially on longer span bridges) as part of the structural analysis and feasibility design study as a means of better understanding a structure's in-service performance to enable the appropriate asset management decisions to be made.

In view of the relatively high value of structures renewals (£405M for 2016/17), consideration has been given as to whether smart monitoring has the potential to defer or reduce renewal spend. Feedback from discussions with Network Rail on this topic was that for the foreseeable future any benefits are likely to be limited and outweighed by the cost of the monitoring.

2.3.2.2 Appraisal

A scenario was developed to test the case for smart monitoring to enable a deferral of bridge renewals. A benefits map shown in Appendix B was produced to aid the development of the CBA. Benefits and costs were assessed over a 60 year period, consistent with WebTAG for rail assets with very long lives.

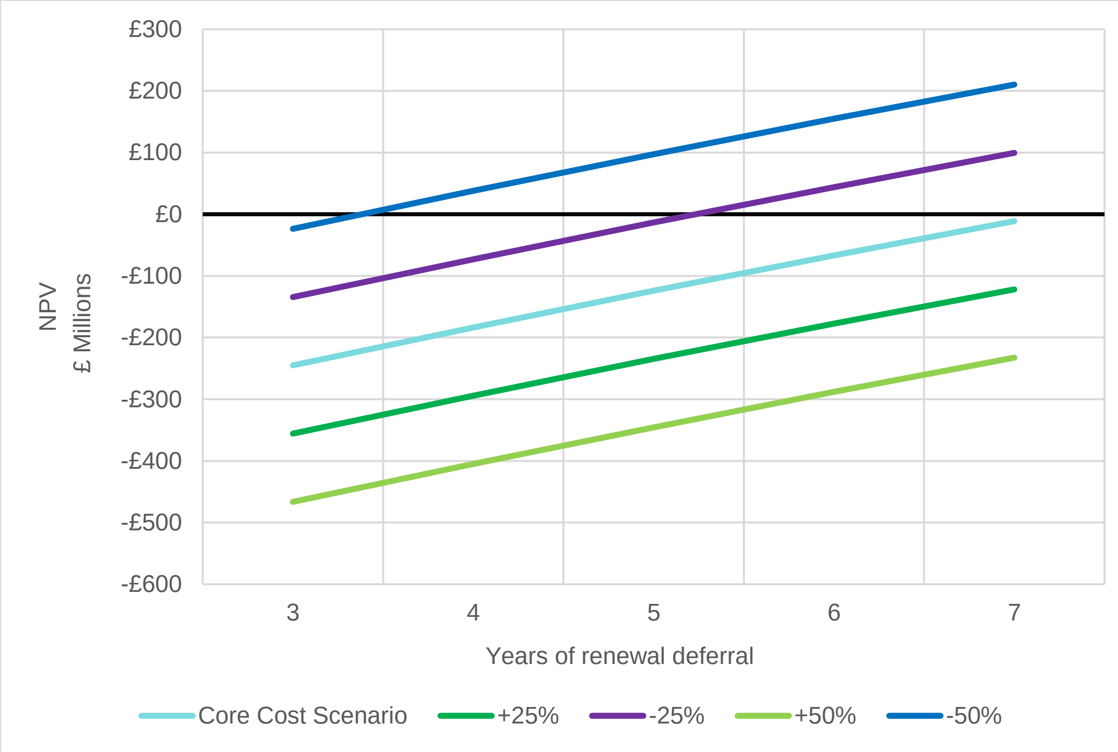
For this scenario, it was assumed that monitoring equipment was installed on bridges scheduled for renewal, and that (for the core case) 20% of renewals would be deferred by an average of five years, with a lower bound capital cost of monitoring equipment of £25k per structure. These assumptions were tested with Network Rail, but they are our figures.

We also undertook sensitivity analysis, testing variations in the total cost of the monitoring and the length of renewals deferral.

The results of this analysis are summarised in Figure 1. Under our core assumptions the NPV is negative.

The NPV is improved under the sensitivity tests which are predicated upon lower monitoring costs and/or a longer period of deferred renewals investment. We estimate that a neutral NPV would be achieved with a 25% reduction in monitoring costs and if this reduction were coupled with an increase in renewal deferrals to seven years, then a positive NPV of circa £200M is forecast.

Figure 1: Total NPV of deferred bridge renewals under differing monitoring costs and asset deferral periods



Although this case study is supported by limited and emerging data, the poor NPV results appear to add weight to the view from Network Rail, that there is unlikely to be a business case for rolling out smart monitoring as a means of extending asset life based on current costs, apart from, potentially, for isolated structures.

Notwithstanding the above results, such a monitoring approach for renewals could be a useful strategy should it become necessary to manage a future surge in asset failures that require a significant increase in future renewal activity. It is conceivable that such a surge could result, for example, as Victorian built metallic bridges approach the end of their fatigue life. A large-scale deployment of this nature could also help to reduce monitoring costs and therefore improve the business case. Investment in data capture and analytical technology across Network Rail's asset portfolios could also reduce ongoing monitoring costs for applications such as the deferral of bridge renewals.

It is recommended that the opportunities that smart monitoring can potentially offer in relation to the deferral or reduction in renewals, be considered as part of a future detailed study into structural health monitoring (as discussed in section 2.3.1.1).

2.3.3 Bridge strike case study

Bridge strikes to rail over road bridges was selected as a case study as it is a high frequency, high cost, and largely predictable problem that affects a limited proportion of the bridge population. It therefore has good potential for benefitting from smart (or smarter) monitoring. A range of monitoring solutions (low tech to smart tech) have been explored.

Appendix section E.3 provides a list of assumptions used to produce a CBA for these technologies. A benefits map shown in Appendix B was produced to aid the development of the CBA.

Figure 2: Example of a Bridge Strike

2.3.3.1 Background

Bridge strikes occur when a high-sided road vehicle, typically a heavy goods vehicle, collides with a low clearance rail bridge.

There are around 3,500 low headroom bridges on the national rail network, of which the majority (circa 2,000) have been struck during the last ten years[7]. Rail over road bridges across the national rail network are typically struck five times a day (currently approximately 1,750 strikes per year[8].).

Bridge strikes often lead to:

- Railway disruptions or closure
- Requirements for bridge inspection
- Road closures and traffic congestion
- Call out of emergency services (police, firefighters, and ambulances)
- Damage to lorries and bridges

[7] Network Rail Bridge Strike Database data (2007/08 to 2017/18 Period 6)
[8] Network Rail Bridge Strike Database data (2007/08 to 2017/18 Period 6)

- Injury, and in the worst-case scenario, loss of life

Bridge strikes also carry a significant rail safety risk, due to derailment associated with bridge deck displacement or collapse. In the absence of interventions, the severity of strikes is expected to worsen as rail passenger numbers increase.

Figure 3 shows the estimated total financial and economic cost of bridge strikes.

We estimate the total cost (financial and economic) of bridge strikes to be of the order of £80M[9] per year in 2016/17, rising to circa £95M by 2035.

Using information supplied by Network Rail[10], we estimate that the financial cost to the rail industry was circa £12M in 2016/17, largely through a loss of passenger fares revenue.

Using data collected for a previous Mott MacDonald study[11] we estimate that the cost to the road haulage industry and its insurers through damage to vehicles and goods was in the region of £30M over the same time period.

As well as the direct financial impacts described above, delays to passengers have an associated economic cost. This is principally through the wasted passenger time, but also through externalities such as traffic congestion and air pollution caused by a modal shift from rail to road. Using analysis provided by Network Rail[12] we estimate that a delay incident which causes £1 of rail fares revenue loss, will also cause a value of time loss of £2.56 and externalities of £0.28. This is an estimated weighted average for Great Britain, and these relative values will vary by Network Rail route section, depending on the composition of train services.

On this basis, the estimated economic cost through a loss of passenger journey time is just under £45M.

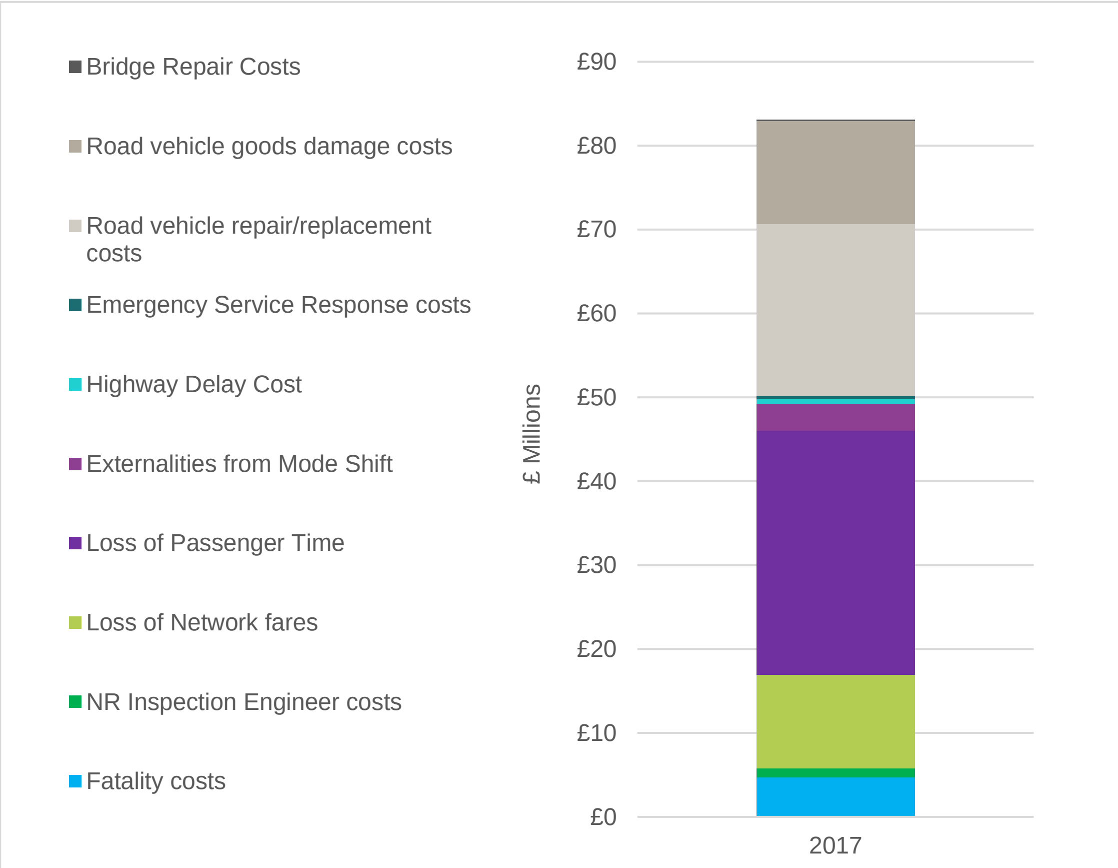
9 Figures are shown in 2016/17 prices and values unless stated otherwise.

10 Network Rail PFPI costs for 2012/13 – 2016/17

11 Mott MacDonald Bridge Strike Study undertaken on behalf of Network Rail (2016)

12 Network Rail analysis of Schedule 8 rates compared to Value of Time Savings and non-user impacts

Figure 3: Estimated financial, safety and economic costs of bridge strikes in 2016/17 (£M)



2.3.3.2 CCTV-based monitoring

The key CBA assumptions for this example are shown in Table 8 (Appendix section E.3.). Data references are as per Section 2.3.2.1.

Network Rail manages the risk of a bridge strike by putting in physical and/or operational measures which depend upon the relative robustness of the structure to withstand a heavy bridge strike. For the highest risk (red) category structures, after a bridge strike, trains will typically not be permitted to cross the bridge until it has been checked by a bridge engineer. For lesser risk category structures, trains may be permitted to cross the bridge at reduced speed.

Technology and Network Rail Standards already allow a CCTV-based monitoring system to be used at the highest risk (red) category structures as a means of allowing trains to cross the bridge at low speed (10mph) in advance of a physical examination by a bridge engineer. Installation of such a system can therefore lead to a significant reduction in rail disruption and passenger delay.

For the purposes of this CBA we have assumed that the system would enable ‘red category’ bridge strikes which currently result in a complete suspension of rail services, (currently around

31% of strikes), to instead be managed by a TSR. We estimate that is broadly the equivalent of around a 30 minute reduction in the duration of delay per strike.

Figure 4 shows the estimated financial and economic cost savings of installing this technology across the 2,000 bridges that have been struck over the last ten years. As can be seen the financial payback[13] for the whole portfolio of bridges is weak in the short term and results in an overall net financial loss of £17M over an assumed 20-year CCTV asset life. The combined financial and economic case over the same time period is stronger however, with a NPV of £31M[14]. The strength of the case varies depending on how often bridges are struck.

The value of the investment varies significantly depending on how frequently a bridge is likely to be struck. To illustrate this point we have grouped all 2,000 bridges into three categories:

- High frequency struck bridges (3 or more strikes per year)
- Medium frequency struck bridges (1-3 strikes per year)
- Low frequency struck bridges (less than one strike per year)

Figure 5 illustrates the difference in the strength of the case when the frequency of bridge strikes in considered, focussing on the financial case. We have selected the financial case as it provides a better illustration of the differences caused by the frequency of bridge strike (ergo delay causing event). As can be seen, CCTV monitoring would only generate a positive financial return over 20 years for the high frequency struck bridges. For this bridge category we estimate total savings of £11.3M and total costs of £3.2M, providing a return on investment in excess of three to one. The resultant financial NPV (net saving) is £8.1M, shown when the turquoise line on the graph reaches the year 2038.

Both the high frequency struck bridges and the medium frequency struck bridges have a positive combined financial and economic NPV of £23M and £1M, respectively, giving a total potential benefit of £24M over 20 years. This relatively modest sum, is reflective of the limited nature of the CCTV-based technology.

The case for each category of bridge could be improved further by targeting the routes with the highest level, and therefore value, of rail traffic. This is also likely to be true for all or most other types of rail asset problems which cause delay to passengers.

[13] Offset loss of rail fares, versus purchase, installation and operating and maintenance costs

[14] All positive impacts, versus purchase, installation and operating and maintenance

Figure 4: Incremental financial and economic impact of CTTV based monitoring, 2016/17 prices

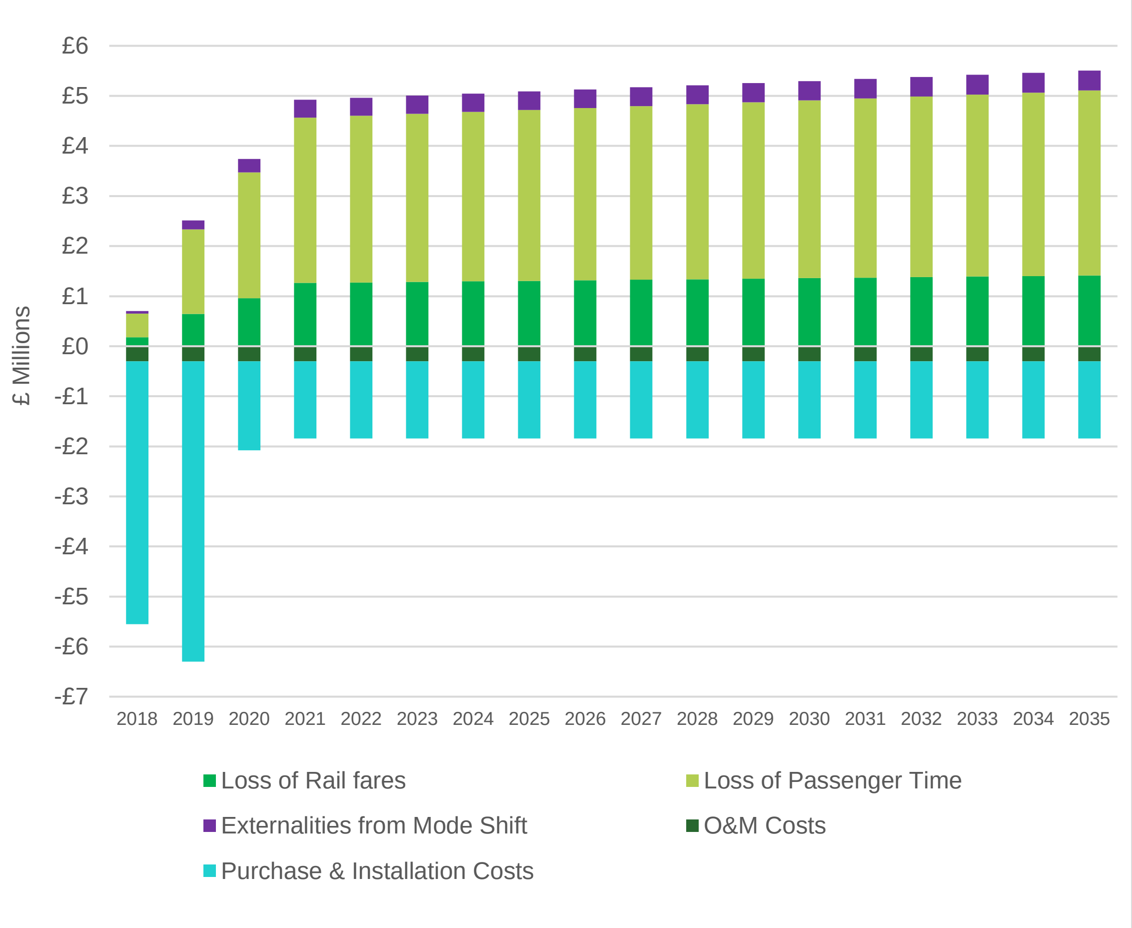
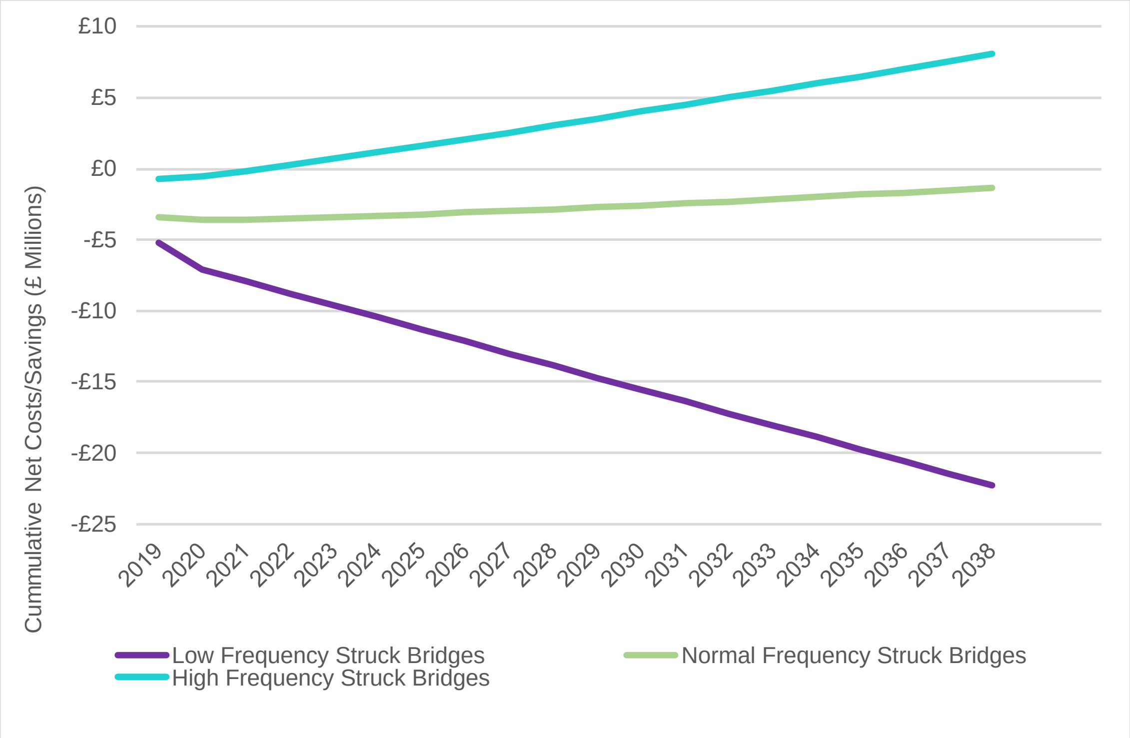


Figure 5: Net cumulative financial payback of CCTV based monitoring, 2016/17 prices



Whilst this is a relatively low-tech application of monitoring, it demonstrates the value of reducing the duration of down time following an asset failure, and the value of monitoring to support assets which fail frequently (in this case the high frequency struck bridges).

It is important to emphasise that this is a basic monitoring technology which, as described previously, would potentially only reduce the impacts of the 'red' category strikes. Better technologies are therefore available to address this problem, which we consider later.

We also understand that a similar system was deployed previously by Network Rail but was discontinued due to difficulties in establishing a cost-effective maintenance regime for equipment on site and a web based IT system. An improved data capture and management system would therefore improve the benefit of this application of monitoring.

2.3.3.3 Monitoring to trigger a warning system

The key CBA assumptions for this example are shown in Table 9 (Appendix section E.3.). Data references are as per Section 2.3.2.1.

An alternative use of monitoring is technology which can detect the height of road vehicles (particularly HGVs and buses) and trigger a warning signal to the driver that a collision is likely.

This technology is not fool proof. Network Rail has worked closely with Transport for London on an installation of a trial system on the bridge over the A205 Thurlow Park Road in London. Despite this investment there have been instances where drivers have ignored or not seen the system and continued on to hit the bridge. Network Rail guidance indicates that only around 40% of strikes may be prevented by this type of technology.

For this CBA we have therefore assumed that 40% of delays associated with bridge strikes could be avoided.

Figure 6 shows the total NPV of the estimated combined financial and economic saving for fitting all bridges in the low, medium, and high-risk categories. Figure 7 shows the impact on the total NPV resulting from variations in the success of the technology and installation and monitoring costs.

Over an assumed 20 year asset life, the financial and economic NPV for the highest risk bridge category has increased from £23M for CCTV monitoring to £197M for monitoring with a warning system. The financial and economic NPV for the medium frequency struck bridges has increased from £1M for CCTV monitoring to £109M for monitoring with a warning system. The NPV for both categories of bridges has therefore improved from £24M to £306M

The category of bridges which are stuck least often still has a negative combined financial and economic NPV (-£170M).

The NPV is sensitive, in particular, to the overall cost of the technology. For example, a 25% reduction in the installation and operating costs would improve the NPV for the whole portfolio of bridges by 33%.

Figure 6: Total Financial and Economic NPV by category of bridge, 2016/17 prices: highway warning system monitoring

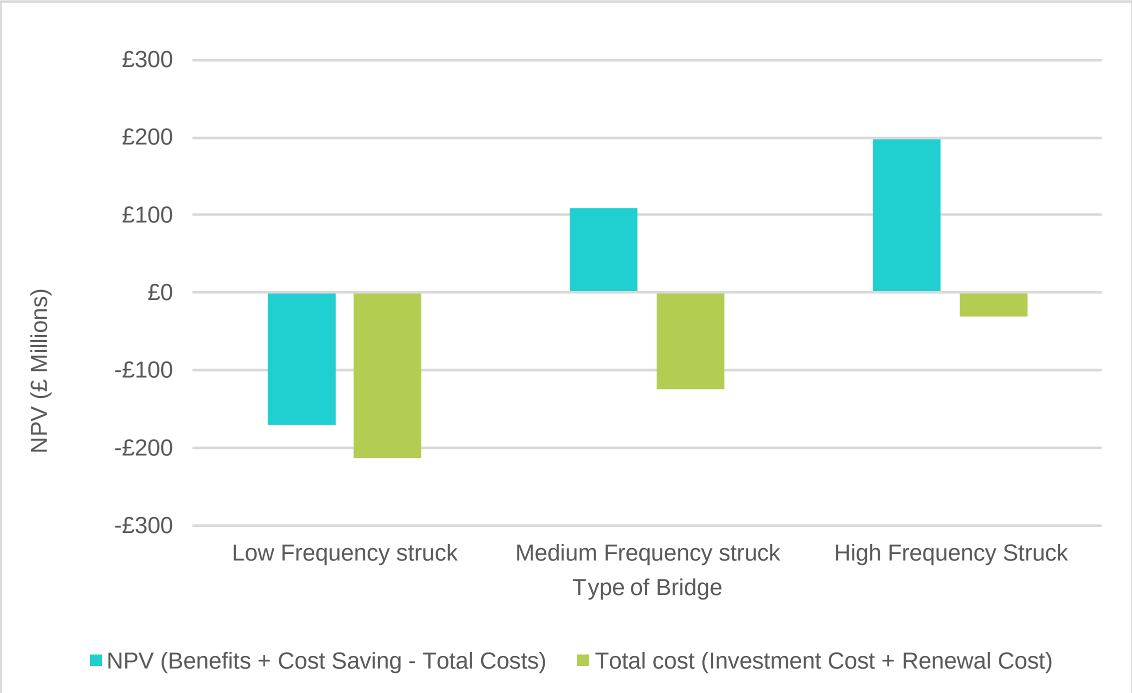
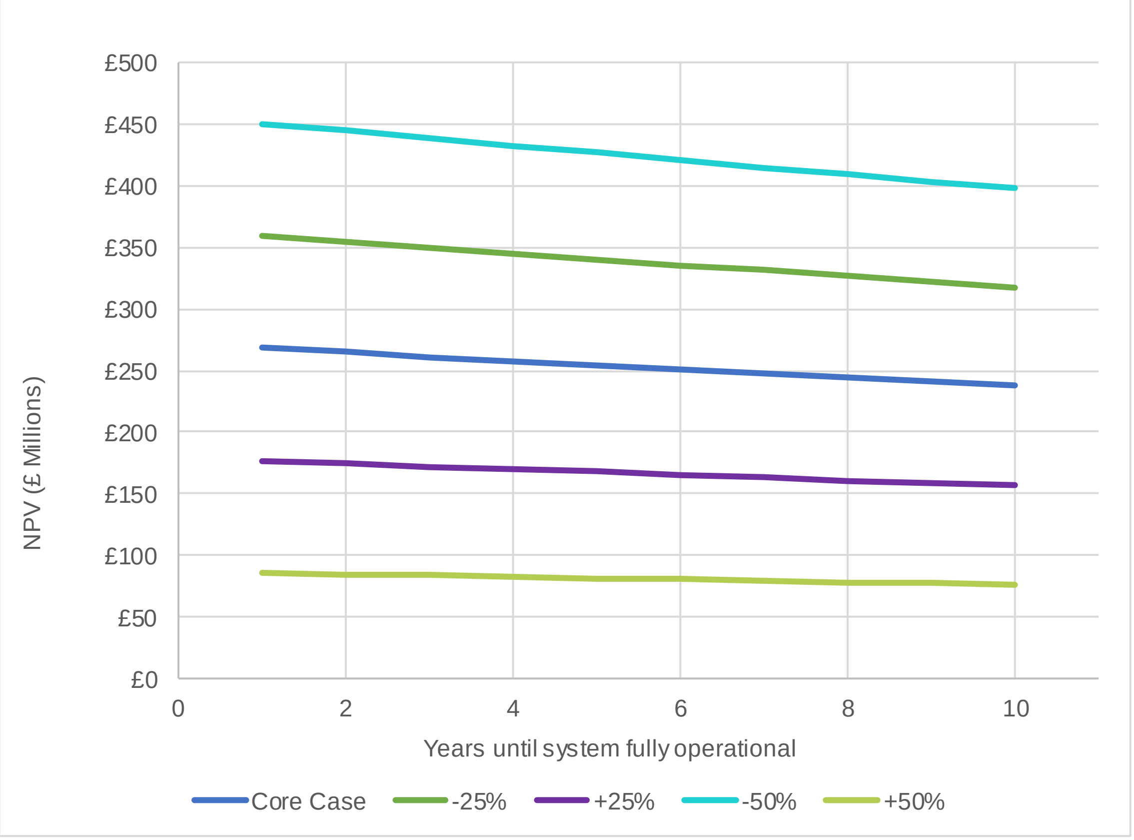


Figure 7: Total Financial and Economic NPV under various cost and operational scenarios 2016/17 prices: highway warning system monitoring



2.3.3.4 Monitoring to automatically stop vehicles

The key CBA assumptions for this example are shown in Table 10 (Appendix section E.3.). Data references are as per Section 2.3.2.1.

The most sophisticated application of monitoring technology would be to pair height detection with an in-vehicle safety system such as a dashboard display or the control of an autonomous vehicle.

This system is likely to be the most effective means of avoiding bridge strikes entirely, however, it would be reliant on understanding the all-round clearance of both the road vehicle and the bridge. In other words, the width and height of both the vehicle itself and its load need to be known or measured.

We are aware that both Volvo and Scania are developing in-vehicle safety systems that will slow down and stop vehicles based on proximity to an obstacle, and understand that Network Rail is closely monitoring these advances in technology.

A system which interacts with autonomous vehicles is most effective means of preventing bridge strikes altogether. As this would be an add-on to technology already within the vehicle, much of the required equipment may already be installed, and only the marginal costs of the additional equipment would need to be covered.

The potential financial and economic savings through monitoring and autonomous vehicle control is the bulk of the value shown in Figure 3, therefore circa £80M per year in 2016/17 prices.

There is also potential for this technology to be adopted more generally for highway structures, which would have financial, economic and safety benefits.

2.4 Monitoring technologies across the GB Rail Asset Base- Network Rail early draft Intelligent Infrastructure Strategic Plan

Network Rail has provided us with an early draft of its Intelligent Infrastructure Strategic Plan for Control Period 6 (CP6, 2019 – 2024)[15]. It is important to emphasise that this is a draft plan subject to change over the forthcoming months.

We understand that the aim of this plan is to improve the availability of GB rail infrastructure by understanding what is likely to go wrong and when, the impact a failure will have on the operational railway, and the appropriate intervention to avoid impacts on the train service. This plan will build on the work undertaken through Network Rail's ORBIS programme and the steps taken during CP5 to move towards data driven asset management.

The plan for CP6 includes:

- Inclusion of performance requirements and failure mode effects and critically analysis into the lifecycle for new product design
- Development of reliability-centred creation of maintenance regimes
- Deployment of infrastructure monitoring technologies
- Delivery of information management systems used in Intelligent Infrastructure processes
- Development of analysis platforms for the data gathered by the above activities
- Development of planning tools to optimise work bank management

Investment in monitoring technology and associated information systems are therefore key components of this plan.

Network Rail has identified the following categories of benefits:

- Reduced maintenance costs
- Fewer service-affecting failures
- Faster recovery during failures
- Increase in workforce productivity

Our bridge strike case study shows that there are significant opportunities for a reduction in service-affecting asset failures, and for a reduction in the subsequent downtime after such failures. The reductions identified in our case study are higher than the figures suggested by Network Rail, but this to be expected as the types of assets and technologies are different.

Our case studies suggest that the opportunities to achieve substantial reductions in maintenance costs and workforce productivity in relation to structures assets are limited. This supports the fact that structures are expected to form only a small part of Network Rail's Draft Intelligent Infrastructure Strategic Plan.

[15] Network Rail early draft Intelligent Infrastructure Strategic Plan, dated 13th October 2017

Network Rail's early draft plan suggests that an investment of circa £380M between 2019 and 2024 could generate, over the same period, a gross saving of £670M and a net saving of £290M. This level of return is broadly reflective of our related case studies

We understand that this investment is likely to be undertaken in two tranches. The first tranche of circa £190M is supported by existing business case work and is likely to go ahead, subject to the availability of funding and agreement from ORR. The second tranche of £190M is subject to further investigation and will depend on suitable business cases being identified.

If both tranches go ahead, the expected ongoing net financial savings are estimated to be in the region of circa £200M per year, five years after the full investment is complete.

We are unable to decompose this headline figure into its component parts. However, it seems reasonable based on the potential for delay cost savings alone, and the evidence from our bridge strike case study. Our assessment suggests a saving over the life of monitoring assets of at least three times the initial investment and ongoing monitoring costs, if the investment is targeted strategically.

The figure of £200M excludes the non-financial benefits which can be monetised in a HMT Green Book appraisal, such as improvements to passenger journey times, reduced traffic congestion and fewer accidents. Our assessment suggests that these benefits can be almost three times as large as the financial savings for technologies which prevent or mitigate disruption to passengers.

2.5 Potential longer-term benefits of monitoring to avoid asset failures

We have conducted a high-level top-down analysis of incident delay codes to illustrate the potential total value of investment in smart infrastructure (monitoring, data capture, analytics) to mitigate delays to passengers.

Total lost fares revenue as a result of delays to passengers caused by issues which are the responsibility of Network Rail is estimated to be circa £870M per year[16]. Of this figure between £350M and £500M is related to asset failures, which is approximately:

- 4%-5% of total annual GB rail fares revenue
- Equal to Network Rail's annual structures renewals budget
- 30% of Network Rail's total annual maintenance budget.

Excluded from this analysis is the majority of the rail fare revenue losses from major infrastructure failures such as landslips and the collapse of structures, as these impacts are infrequent occurrences shown in a separate set of statistics.

As shown in the bridge strike case study, delays to passengers through infrastructure failures have economic dis-benefits and other impacts which can be monetised as standard in a HMT Green Book/ DfT WebTAG economic appraisal. Applying the ratio to fares losses used in the bridge strike case study, we estimate that in addition to the £350M - £500M stated previously there are passengers' value of time losses worth £0.9bn - £1.3bn[17] and non-user impacts (mainly through a model transfer from rail to road) of around £0.1bn[18]. This is £1.3bn - £1.9bn in total.

[16] Network Rail PFPI costs for 2016/17

[17] Network Rail analysis of Schedule 8 rates compared to Value of Time Savings and non-user impacts

[18] Network Rail analysis of Schedule 8 rates compared to Value of Time Savings and non-user impacts

Network Rail has supplied an estimate of lost fares by (circa 115) incident reason categories. We have examined each category and considered whether data-driven monitoring and asset management could reduce or mitigate the number of and/or delay caused by each type of incident. This is therefore a high-level top-down analysis.

Where an incident category was judged to be in-scope we applied the following assumptions to estimate the reduction in delay costs:

- A 15% reduction in the number of incidents for all in scope incident categories (excluding bridge strikes). Therefore a 15% reduction delay associated with these categories.
- A 45% improvement in recovery time following an incident, for the remaining 85% of delay caused by the in-scope categories.
- Zero bridge strike related delays (from the bridge strike case study – autonomous vehicles).

We have considered Network Rail's evidence when forming these assumptions, but they are our figures.

We estimate that up to £0.6bn could be saved annually over the longer term through investment in monitoring and data-driven asset management, split £0.16bn through increased rail fares revenue and £0.44bn through economic impacts (avoided lost passenger time and externalities). The latter figure was derived using the proportions shown in the bridge strike study, and described earlier in this section.

The figure of £0.6bn excludes the impacts of changes in future passenger numbers and the number of trains services on the network. Both could potentially increase the benefit further.

3 Water Sector Analysis

3.1 Introduction

The water industry is an asset intensive sector. Roughly two thirds of all expenditure is attributed to asset maintenance and asset enhancement. Each five-year period (so called 'AMPs' – the sector is currently in 'AMP 6') sees approximately £25bn spent on maintaining and improving assets. Before the introduction of total expenditure (Totex – the sum of capital and operational expenditure over a five-year AMP) at the last price review, capital maintenance of assets represented roughly 60% of all capital expenditure.

This expenditure has driven significant improvements in performance both across water and sewerage. Drinking water compliance with quality standards is now consistently in excess of 99.9% and 99% of water at beaches or lakes is now rated as at least sufficient. There are now over 200 Blue Flag beaches and customers are five times less likely to suffer an interruption to their water supply than at privatisation in 1989[19]. The current sector model has therefore delivered significant benefits for customers and the environment.

However, the sector is not without its challenges, many of which are directly related to asset management or driven by asset management practices. These challenges have been recognised by Ofwat and they form the backbone of the forthcoming price review.

- Resilience – ensuring that our water and environment can cope with, and recover from, disruption in order to maintain services vital services for customers.
- Customer service – encouraging customers to be more active participants and ensuring companies stretch themselves to deliver more for their customers.
- Affordability – ensuring companies do more to deliver value for money with affordable bills both now and in the future and that vulnerable customers are protected.
- Innovation – investing in new technologies and working smarter to deliver benefits for customers and the environment.

The sector is heavily asset-centric in part due to the fundamental nature of water and sewerage. As an entity it is heavy and difficult to transport. As a summary the sector has:

- 1,100 water treatment works
- 349,000km of water mains
- 545,000km of sewer pipes
- 6,300 sewage treatment works

All of this requires high levels of investment and some studies estimate that a further £96bn of capital investment is needed over the coming 20 years.

Spending on R&D in the sector as typically been quite low. In his review of markets and innovation in the water sector Professor Martin Cave noted that[20]:

"While many companies see research and development as an important driver of their business, support for such activity, is very variable and ranges from 0.02 per cent to 0.66 per cent of turnover. A minority of companies characterise themselves as followers, relying on others to test and implement new technologies. Comparisons of international data suggests that the UK is

[19] Ofwat (2015) Sector challenges and Water 2020 - Cathryn Ross, Chief Executive'

[20] Cave (2009) *Independent Review of Competition and Innovation in Water Markets: Final report*. DEFRA. Available online

responsible for fewer innovations per capita than other countries such as Australia, Germany, the Netherlands, Spain and the United States."

This framework of relatively low and fragmented levels of innovation across the sector is also set against a backdrop of real cost pressures. Companies have reduced baseline operating costs 21% since privatisation in the 1980s and at the last two price reviews average bills have fallen. Yet much of the 'low hanging fruit' in efficiency terms has now been exhausted. The sector will need to work smarter to continue achieving efficiency levels that are cognisant of wider, strategic affordability goals and a growing desire for legitimacy in profits and dividends.

There is therefore an urgent need for water companies in England and Wales to do more with less. Smart technology that enables better asset management will be a key enabler for the sector to address these challenges. The opportunity presented by a more proactive approach, built upon information from smart water networks is estimated at £2.7bn per year for European water utilities[21]. Technology costs are starting to reduce rapidly across all categories required for smart infrastructure, with relatively mature digital technologies such as cloud services for data management achieving 6-8% cost reductions per year over the last decade[22] with the underlying hardware cost reducing at 15% per year[23].

However, there are significant challenges to overcome – particularly in relation to existing information management and shortcomings in data availability. Recent investment to improve information systems and enable integration of operational data at one water company found that 80% of the available data did not meet their own requirements.

Current monitoring solutions are fragmented, with limited standards for sensor data or communications. Where information requirements do exist, governance is weak, resulting in poor quality and conflicting records that require significant data cleansing before use. There is also a lack of user-friendly applications that combine real-time and static data for visualisation, particularly for use by operators[24].

The new technologies reviewed in this study need to be considered in this context, where significant investment in back-office IT systems, analytics and suitably skilled staff will be required to integrate them with existing operational systems. As information management improves many of these marginal costs for implementing technologies that provide additional data streams may reduce.

3.2 Case study selection

Review of data available from NIC

Through prior engagement with water companies the NIC had identified two possible case studies for further investigation:

- Anglian Water – smart meter data from Shop Window pilot deployment; and
- Southern Water – universal metering programme.

Review of other data sources

The UK Water Partnership's LITSoN (Linking Innovation to Societal Needs) database summarises the current research, development and innovation projects of UK water companies

[21] Smart Water for Europe: https://sw4eu.com
[22] CNet (2014) Google on cloud storage pricing: 'Follow Moore's Law'. Available online
[23] Backblaze (2017) Hard drive cost per gigabyte. Available online
[24] Smart Water for Europe: https://sw4eu.com

representing over 70% of the regulated market[25]. This database has been reviewed to identify new smart monitoring technologies that could support better asset management and increased efficiencies in the water sector. Further projects were identified from Mott MacDonald's knowledge of the UK water industry, resulting in over 50 potential case studies and pilots, listed in Appendix A.

Case study shortlist

A shortlist of four case studies to investigate further was selected based on the following criteria:

- Provides broad coverage of the water sector, including 'infrastructure' (below-ground assets, primarily networks) and 'non-infrastructure' (above-ground assets, primarily treatment works); clean water and wastewater.
- Includes a wide range of benefits, including direct operating cost efficiencies and wider enhancement of social value and natural capital.
- Reached a sufficient level of technological maturity that data may be available from pilot studies undertaken by water companies.
- Trialled by multiple water companies, to maximise the opportunity to collect relevant data within the project's timescale constraints, and test assumptions and sensitivity on the applicability of costs and benefits at national scale.

The case study shortlist comprised:

Smart metering – use of fixed network Advanced Metering Infrastructure (AMI) to enable remote meter reading and to provide improved consumption data for customers and the water company.

Water network sensing – use of permanently deployed sensors to improve leak detection and pressure management.

Smart wastewater network – use of sewer level monitoring to enable real-time control for improved operations, potentially combined with real-time weather data for forecasting.

Wastewater process optimisation – use of energy monitoring at plant level to create real-time visibility of plant performance.

Details of engagement with the water companies on each case study are provided in Appendix A. Data was received on two case studies relating to smart metering and permanent acoustic logging (a specific application of water network sensing), which are described in the following section. Insufficient data was received to develop a cost benefit analysis for the two wastewater case studies, therefore these have not been considered in this study, but do merit further investigation.

A benefit map was developed for each case study considered, to outline the benefits and how they derive from improvements to asset management activities. These are included in Appendix B.

3.3 Case study analysis

3.3.1 Smart metering

Water scarcity is an increasingly pressing issue in many parts of the UK, and particularly the South-East. Many water companies are therefore exploring enhanced demand management options to reduce consumption and leakage and to help balance future water supplies against demand. Household revenue smart metering is an area of particular focus; this technology

[25] UKWP (2017) LITSoN Pilot – available online

increases the frequency of meter readings and provides better information on water consumption in order to encourage customers to use less water and reduce their bills. The meters are also equipped with a leak alarm which activates when water runs continuously through the meter enabling customer leaks to be identified and repaired more quickly.

There are two principal smart metering technologies:

- Automated Meter Reading (AMR) – customer water consumption data is read periodically using 'drive-by' technology to provide the company with retrospective daily, weekly, or monthly statistics.
- Advanced Metering Infrastructure (AMI) – meters are read automatically using a fixed telecoms network. Consumption data can be made available on a daily basis to customers.

Southern Water has implemented a universal metering programme that started in 2010 based on AMR technology. Since then AMI cost reductions have led various companies, including Anglian Water and Thames Water, to trial or start deploying the technology.

Anglian Water is currently installing 7,500 AMI meters (80% complete) in their Newmarket Innovation Shop Window, a live part of their network the company uses to test new technologies and approaches. Digital readings are collected automatically at hourly intervals for operational purposes (e.g. network management) and shared with customers daily through a web-based portal. This puts customers in control of their bills, helping them reduce their water consumption through providing more regular and detailed information via comparison with their peer group.

We used Anglian Water's case study to develop scenarios which were applied to other UK water companies in the CBA for this technology. Three alternative metering scenarios were identified, and for each water company compared to a base case which assumes the installation of a mix of 'dumb' and AMR meters according to that company's preferred Water Resources Management Plan (WRMP14). The CBA therefore evaluates the return on investment for smart metering compared to 'business as usual' plans for metering – which vary significantly between water companies in different regions.

The cost and benefit categories included in the CBA were:

- Meter purchase, installation, and replacement cost
- Reading technology and meter reading activity
- Telecommunication systems and back-office IT
- Operational activity and maintenance
- Customer demand reduction
- Leakage reduction
- Deferral of investment (water and wastewater, including carbon)
- Customer call reduction
- Hot water energy saving (including carbon)
- Insurance cost reduction
- Environmental and social benefit

Benefits were only included in the CBA where there was sufficient evidence to quantify them from the Anglian Water trial or other industry data. Possible additional benefits that we were not able to quantify in this analysis include:

- Allocative efficiency from improved deployment of water resources

- Network optimisation reducing risk of failure to meet level of service (e.g. calm networks[26])
- Improved targeting of renewals producing incremental improvements in asset health
- Customer experience, including peace of mind over future bills, improved debt management
- Zero flow stop detection (identifying properties that were thought to be empty, but should be paying water bills)
- Social care through services to monitor vulnerable customers

Work is ongoing by Anglian Water and other companies to quantify these wider benefits, in particular calm networks from improved optimisation using smart meter data.

Anglian Water's emerging customer consultation data also shows that customers are strongly supportive of having smart meters to increase awareness of use, and decrease consumption. Although stated preference Willingness to Pay (WTP) data for this smart metering benefit was available for their customers, it has not been included in this CBA. That is because in this appraisal all of the costs and benefits are ultimately passed through to the customer, resulting in a risk of WTP data double-counting the benefit of reduced customer bills. This differs from the CBA undertaken by water companies, where WTP is used to inform an appropriate balance between levels of service and customer bills in Ofwat's regulatory process.

We considered the following scenarios in the analysis:

- **Scenario 1:** Current costs based on supplier quotes and UKWIR estimates[27], including hardware, a private fixed telecoms network, data storage and analytics. Average benefits quantified from early results of Anglian Water's case study.
- **Scenario 2:** Potential future cost reductions for current technologies from increasing competition and national economies of scale. Assumes greater reductions in customer demand and leakage from improved data analytics.
- **Scenario 3:** Future Internet of Things networks replace private fixed telecoms, reducing investment required from water companies. Cost of data management and storage continues to fall in line with historic trends for cloud services. Alternative tariff structures further reduce consumer water usage.

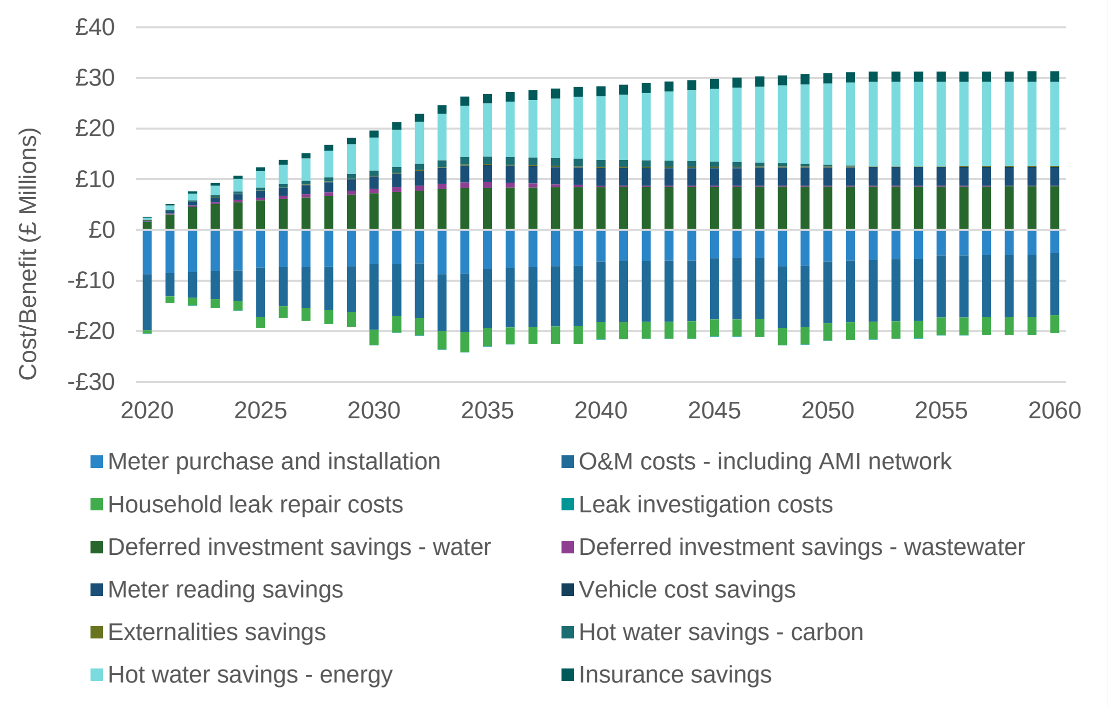
The resulting profile of costs and benefits over the 40 year appraisal period[28] for installing smart metering across an example company is shown in Figure 8. It demonstrates the assumed 15 year deployment period for smart metering as well as forecast future growth:

[26] Improved understanding of the distribution network leading to better operation that reduces or prevents negative impacts such as pressure transients, which can in turn cause water main bursts and discolouration.

[27] UKWIR (2012), Smart Metering in the Water Sector Phase 3 - Making the Case (12/CU/02/13)

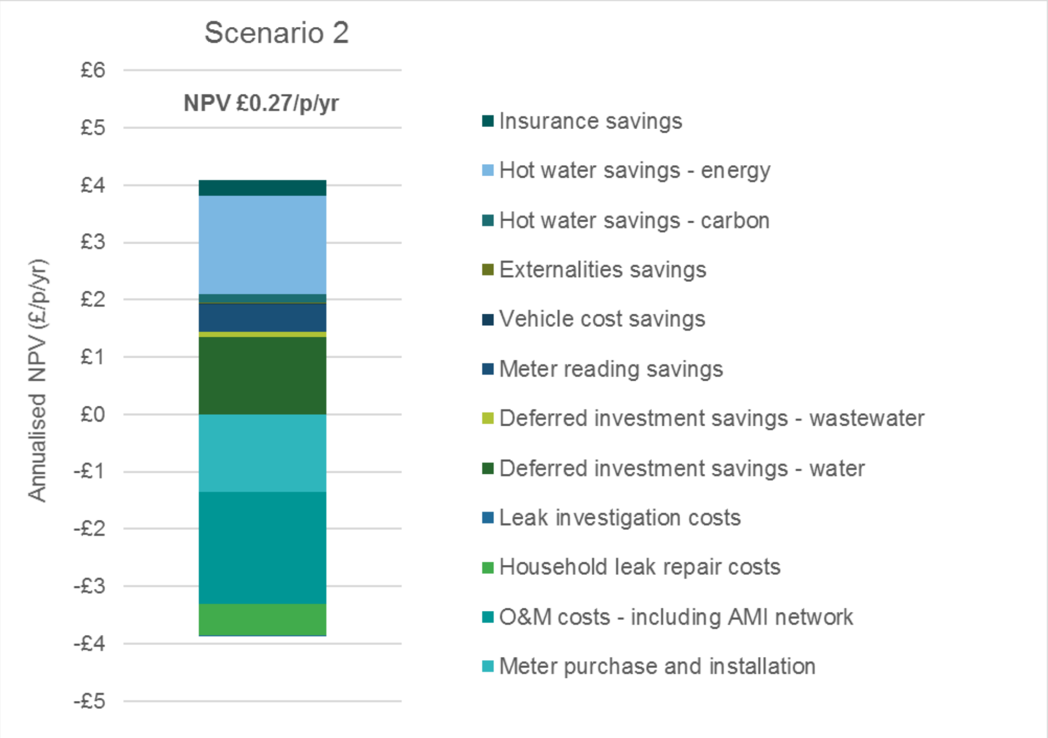
[28] *Ibid.*

Figure 8: Estimated financial and economic costs and benefits of smart metering Scenario 2



The resulting annualised net present value is shown in Figure 9, illustrating the breakdown by cost/benefit category.

Figure 9: Estimated annualised costs and benefits for smart metering Scenario 2



It is important to note that this appraisal includes wider societal and environmental costs and benefits in addition to those that can be included in the water companies' regulatory business plans. These include energy costs associated with reduced consumption of hot water and savings on insurance premiums from improved customer-side leakage detection reducing the likelihood of escape of water claims. These wider economic benefits typically account for over 50% of the total benefit (depending on scenario and water company). This highlights the importance of regulatory mechanisms, such as outcome delivery incentives, that encourage companies to invest where there is a strong economic case to do so.

The results of the three scenarios are compared in Figure 10, for a selected company. The values are presented at 'per property' level over 40 years and have been discounted. It demonstrates the impact of reduced technology costs, and increased water savings across the three scenarios on delivering a positive return on investment.

Figure 10: Estimated financial and economic costs and benefits of smart metering per property per year, across all scenarios. NPV 2016/17 prices and values

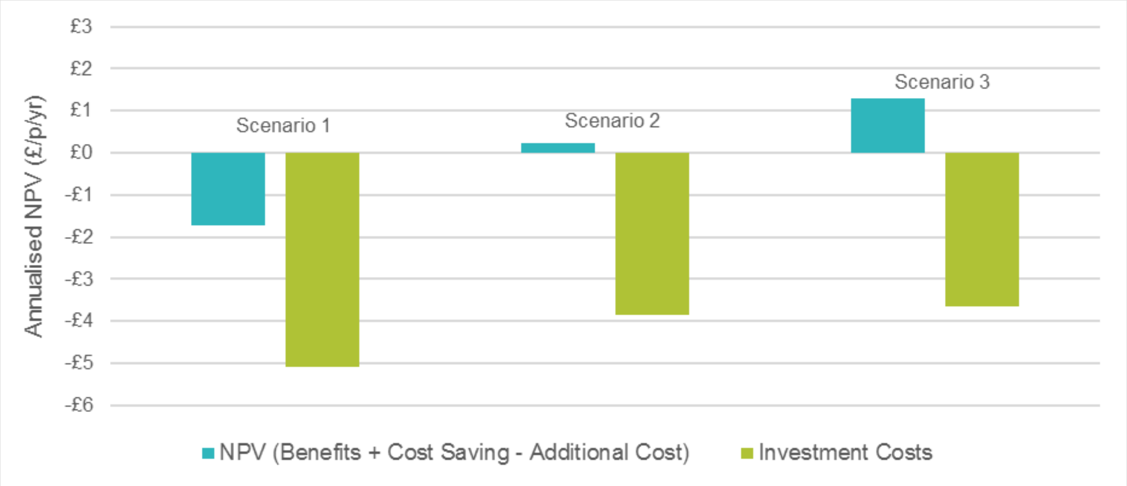
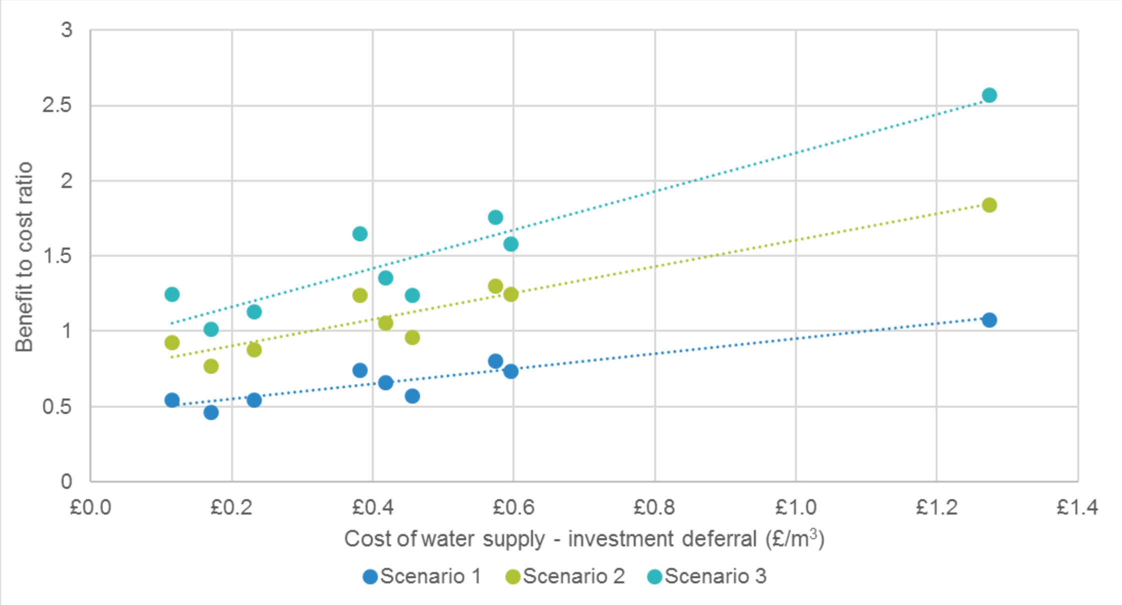


Figure 11 shows the comparison of benefit to cost ratio (BCR) values plotted against long-run marginal cost of water supply for the different companies considered in the CBA. This demonstrates that implementation of smart metering would be more beneficial for companies with a higher marginal cost of supply, but the return on investment is relatively insensitive to this cost. Significant differences are, however, seen between the three scenarios demonstrating the impact of achieving greater water savings through customer engagement and improved analytics for leakage detection, as well as the cost reductions assumed for large-scale deployment.

Figure 11: Benefit to cost ratios for different water companies under each scenario



The CBA results are summarised in Table 4, which demonstrates that smart metering could offer a total lifetime net saving of approximately £600M to £1.5bn, allowing for the future technology cost reductions, and greater consumption and leakage reductions, included under scenarios 2 and 3. These totals assume that in each scenario smart metering is only implemented by those companies that would generate a positive return on investment. It should be noted that these potential savings are based on preliminary results from pilot-scale deployment of smart meters. There is therefore significant uncertainty in how the costs and benefits will transfer to national scale.

Table 4: Estimated NPV and payback periods for smart metering

	Scenario 1	Scenario 2	Scenario 3
NPV per company (£M)	-245 to 18	-80 to 148	5 to 303
Annualised NPV per property (£/p/yr)	-2.74 to 0.43	-0.90 to 3.36	0.07 to 5.87
Total NPV (£M)	18	598	1,524
Benefit to cost ratio (BCR)	0.5 to 1.1	0.8 to 1.8	1.0 to 2.7
Companies with BCR > 1	1 or 10% (of total)	5 or 60%	9 or 100%
Payback period (years)	27	11 to >40	7 to 34

The wide ranges in results for each scenario demonstrate that the economic case for smart metering is highly company-specific, delivering benefits from £0.50p to £2.70 per £1 spent across the three scenarios. This is primarily due to the varying marginal cost of supply of water between companies, but is also a function of factors such as existing and planned meter penetration. As discussed earlier, these values do not include various wider benefits such as calm networks, opportunities for system optimisation and customer valuation of improved visibility of water consumption, which might increase the return on investment across all scenarios. Despite this, under scenario 3 smart metering becomes cost-beneficial for all companies considered.

3.3.2 Permanent acoustic logging

Since the mid-1990s the water companies in England and Wales have reduced the total volume of water leaking from their networks by 37%[29]. This has been achieved through an active approach to leakage control, including the development of more intelligent technologies that locate leaks quicker and more accurately before they become visible, as well as improved pressure management and asset renewals investment. As a result, many companies now operate at or below their Sustainable Economic Level of Leakage (SELL), which is the point at which further reductions are not economically viable using current leakage reduction methodologies.

In preparing their Water Resource Management Plan 2019 (WRMP19) submissions, companies were asked by the regulators to develop strategies that reduce their leakage levels by 15% in volumetric terms[30]. This requires implementation of innovative techniques and new technologies. One such example is permanent acoustic logging, with Affinity Water deploying 20,000 loggers across the 25% of its network that is most prone to leakage, between January and May 2017.

The loggers are installed at 200-400 metre intervals on distribution mains and “listen” to vibrations on the pipe. Data is automatically sent to the control room from the logger (using GPRS cellular communication and SMS. Once installed, there is no need to visit the unit again apart from to change the battery every 5 years. Each unit is tagged with its GPS location, so the information it provides can appear on a map and feed into the user’s GIS system. The analysis is aimed at detecting a consistent noise which may be a leak; when such a noise is detected, it sends an alarm together with an audio file to the utility technician. The audio files from two loggers either side of a leak can provide an accurate indication of where the leak is located. This helps the workforce act on the information as quickly and efficiently as possible. These devices are particularly useful in identifying quieter, and therefore less easily detectable, leaks that are often the largest, therefore helping further reduce leakage levels.

The costs and benefits categories quantified in the analysis included:

- Acoustic logger purchase, installation, and replacement cost
- Operational activity and maintenance
- Deferral of investment
- Leakage detection activity savings
- Customer call reduction
- Environmental and social benefit

Benefits were only included in the CBA where there was sufficient evidence to quantify them from the Affinity Water trial or other industry data. Possible additional benefits that were not quantified include:

- Reduced likelihood of loss of supply and economic benefits to customers of faster resolution
- Improved targeting of renewals producing incremental improvements in asset health

We considered the following scenarios in the analysis:

- **Scenario 1**: Current costs of deploying permanent acoustic loggers based on Affinity Water’s case study.

[29] Mott MacDonald analysis of water company June Returns data and DiscoverWater portal

[30] Ofwat (2017) Delivering Water 2020: Consulting on our methodology for the 2019 price review

- **Scenario 2**: Future Internet of Things technology extends logger battery life, and together with economies of scale, reduce technology cost.

An alternative was also considered where operational cost savings were reinvested to deliver further reductions in leakage beyond current performance. However, the impact of reducing marginal gains resulted in consistently lower NPVs than for the above scenarios. If substantial leakage reduction targets are established as part of the WRMP19 process, this scenario could be reconsidered against the baseline of alternative options to meet those targets.

Figure 12 shows the estimated financial and economic cost saving of installing this technology for a selected company under Scenario 1. It demonstrates the assumed five year deployment period with recurring logger replacement every 15 years.

Figure 12: Estimated financial and economic costs and benefits of acoustic logging Scenario 1. NPV 2016/17 prices and values

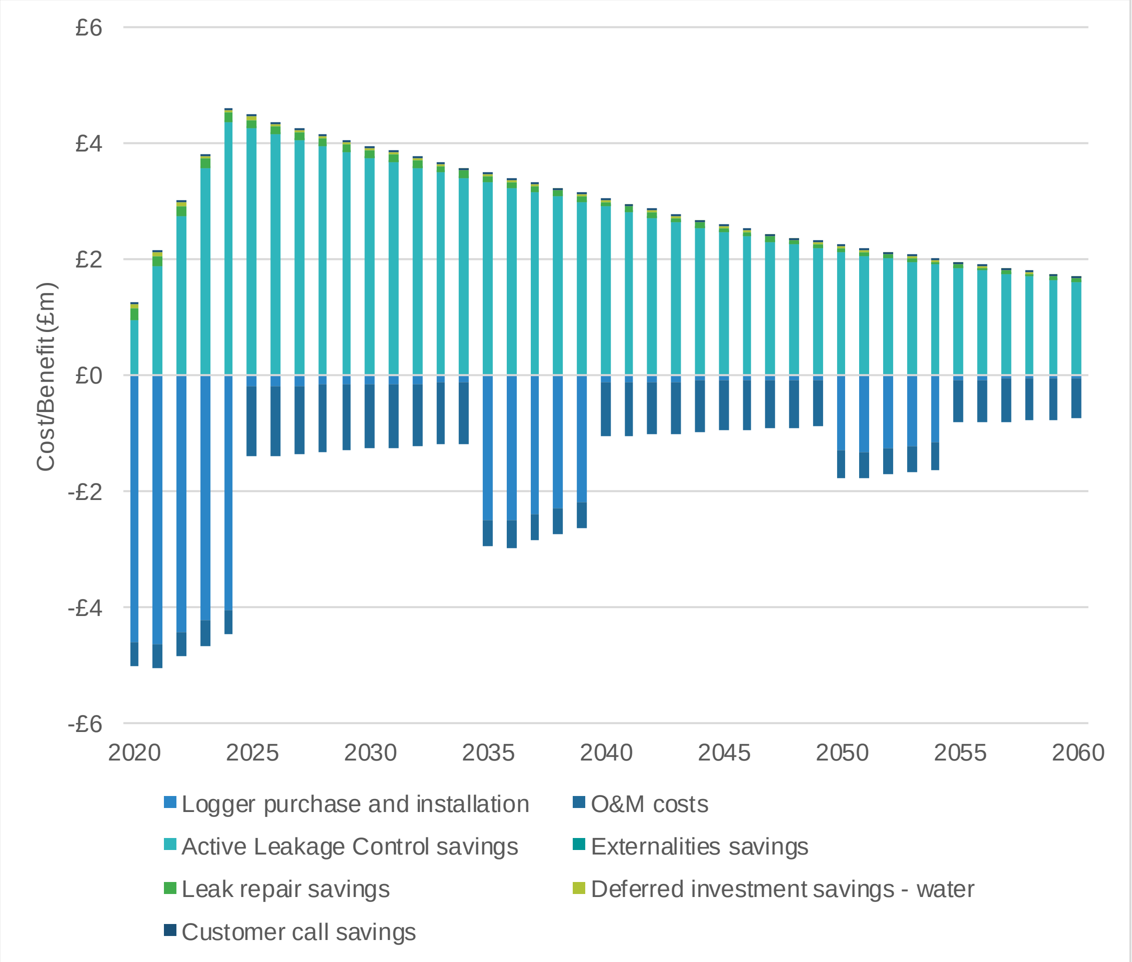
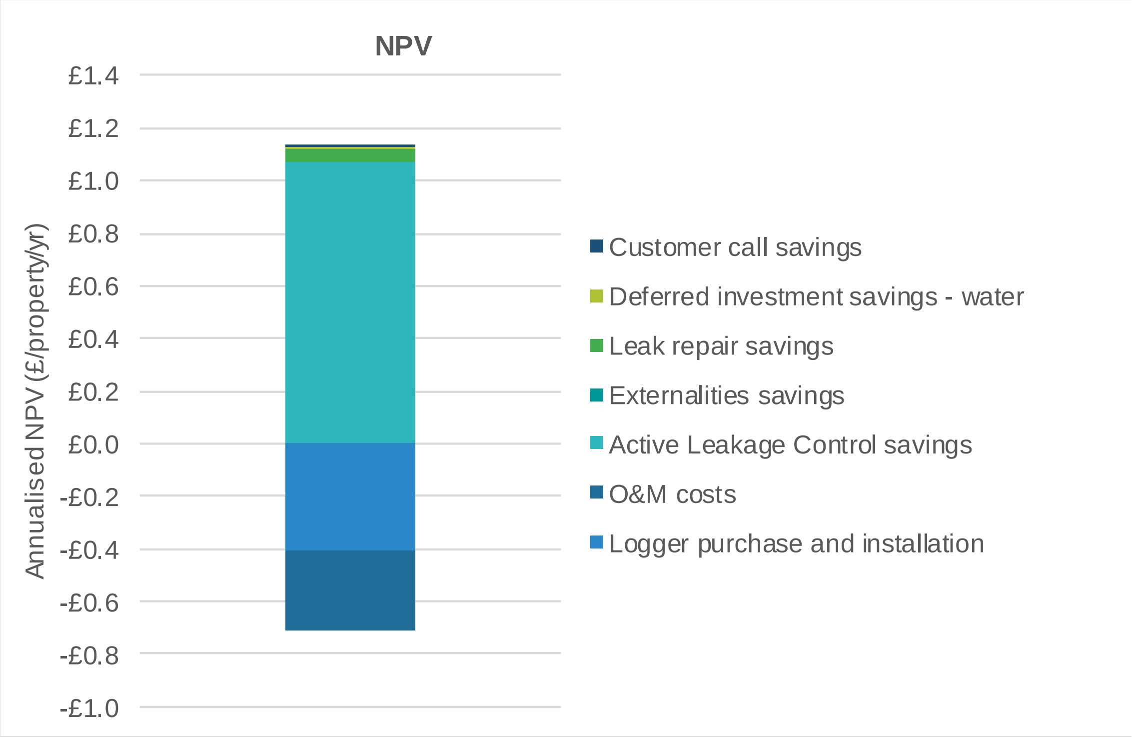


Figure 13 illustrates a breakdown by cost/benefit category for Scenario 1, with a resulting annualised NPV of £0.42/p/yr for the company presented here.

Figure 13: Estimated costs and benefits by category for permanent acoustic logging Scenario 1



It is evident that the primary benefit is in the savings from Active Leakage Control (ALC) through improved efficiency of leakage detection – in this case it accounts for 95% of the benefit. The potential return on investment is therefore highly sensitive to the ALC savings achieved. by examining the impact of a +/-25% change in ALC savings on the resulting benefit to cost ratio.

Under the core scenario the technology is cost-beneficial for four companies (i.e. the BCR is greater than 1). A 25% increase in ALC saving would make it cost-beneficial for six companies, whereas a 25% decrease would reduce that to a single company.

The CBA results are summarised in Table 5, which demonstrates that permanent acoustic logging could offer a total lifetime net saving of approximately £100M. This assumes that in each scenario permanent acoustic logging is only implemented by those companies that would generate a positive return on investment. There is also significant uncertainty in how the costs and benefits may transfer to national scale from this pilot-scale deployment, and what impact revised leakage targets under WRMP19 might have on these results.

Table 5: Estimated NPV and payback periods for acoustic logging scenarios

	Scenario 1	Scenario 2
NPV per company (£M)	-50 to 44	-32 to 52
Annualised NPV per property (£/p/yr)	-0.38 to 0.56	-0.24 to 0.60
Total NPV (£M)	94	112
Benefit to cost ratio (BCR)	0.3 to 1.7	0.4 to 2.0
Companies with BCR > 1	4 or 40%	6 or 60%
Payback period (years)	8 to >40	6 to 21

There is a wide range in the results between companies, with permanent acoustic logging delivering benefits from £0.30p to £2.00 per £1 spent. Even allowing for potential future cost reductions in scenario 2, the technology would only be cost-beneficial for 60% of companies. This highlights that for those companies with relatively low ALC budgets the technology is unlikely to become competitive until higher investment in leakage reduction creates greater opportunities to achieve operating cost savings.

3.3.3 Smart Water Networks for Europe

The Smart Water Networks for Europe project[31] consists of a series of connected pilot projects focusing on leakage and water quality management, energy optimisation and customer interaction. In the UK, Thames Water operate a demonstration site in Reading that serves 89,000 commercial and domestic properties and includes a combination of smart meters and network pressure sensors, building upon investment to improve asset data and information systems. Visualisation tools help operators identify energy hotspots and machine learning algorithms highlight unusual pressure events to improve network operation.

Although targeted as a case study in this review, unfortunately it was not possible to obtain specific data from the project due to our limited timescale, coinciding with a particularly busy time for water companies preparing draft WRMP19 submissions. Further engagement is recommended with Thames Water, Syrinix and wider project partners to obtain the necessary cost and benefit data for the analysis – particularly due to its integrated nature, which is expected to highlight the additional benefits of combining information from multiple monitoring technologies over and above each taken in isolation.

3.4 Wider application of smart monitoring technologies

We have collated an extensive list of over 50 case studies on smart monitoring technologies in the water sector (Appendix A) during the study. This demonstrates the significant interest and perceived value to the UK water sector, however the majority of these are still in research and development or undergoing demonstration and pilot trials.

The CBA results from both evaluated case studies suggest that the cost of implementation will prevent universal deployment by all water companies in the short term. However, both technologies provide a positive NPV for selected water companies under the scenarios considered.

In addition to the benefits described in Section 3.3, it is acknowledged that there are likely to be wider potential benefits that were not demonstrated in these specific trials, and for which no data was available to monetise them in the CBA calculations. Many of these wider benefits are also difficult to attribute to a single technology as they may result from combining information

[31] https://sw4eu.com/

from multiple data sources. This will become more feasible as companies develop increasingly smart asset bases and invest in improving asset data, analytics and supporting information systems to break down operational siloes between legacy applications.

3.4.1 Optimising system efficiency

Increased data availability enables optimisation across multiple timeframes. At the macro scale allocative efficiencies are possible through better targeting of water resources, balancing resources, and storage levels with annual demand profiles throughout the year that rely upon granular smart meter consumption data and improved understanding of leakage from network sensors. This will help companies maximise the use of cheaper water resources, while maintaining required levels of service and resilience.

At the micro scale, more granular flow data from smart monitoring technologies will improve understanding of how the network is used, enabling changes in production and flow allocation to maximise use of the most efficient parts of the system and make strategic use of storage capacity through dynamic, real-time control. Detailed understanding of daily demand patterns will enable cost efficiencies through managing supply in real-time, optimising energy consumption by scheduling activities for minimum cost depending on rates at different times of day or adjusting dynamically to energy pricing signals. In a similar example, Yorkshire Water saved an estimated £0.9M per year across 12 sites by optimising sewage pumping to maximise use of low electricity rates overnight during a smart wastewater networks trial[32].

Better understanding and controlling volatility of flows will help deliver calm networks, with associated benefits in level of service (e.g. reduced risk of discolouration, fewer dead zones resulting in lower water quality risks) as well as preventing bursts, leading to reduced leakage, loss of supply to customers and economic impacts from disruption to traffic and flooding. The availability of near real-time network data can also be used to improve contingency planning and enables faster responses to events, potentially reducing the duration of interruptions in supply to customers. Importantly, more detailed information on customer consumption patterns will enable companies to identify anomalous consumption arising from internal plumbing losses or wasteful consumption and notify customers accordingly to help reduce their bills and demand on water resources.

There is significant potential to improve the efficiency of water and wastewater treatment, with energy and chemical consumption accounting for approximately £18bn in operating expenditure globally[33], and targeted investment in monitoring technologies can deliver operating cost savings of up to 30%[34]. There can also be wider benefits in deferring investment for additional capacity, providing greater certainty in meeting water quality standards or wastewater discharge consents and enhanced resilience from improved asset management. A portfolio of ‘spend to save’ Totex reduction projects was identified as part of this review within Southern Water’s Optimisation team, but unfortunately it was not possible to obtain the data necessary for CBA within the required timeframe. It is expected that similar projects could be identified across multiple water companies to provide robust data to assess opportunities for process optimisation.

3.4.2 Reducing leakage

Opportunities were identified in both case studies to reduce leakage through improved targeting of detection efforts using data from smart meters and permanent acoustic loggers. Further

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[32] OSISoft (2017) Yorkshire Water case study – SWAN Research. Available online

[33] Media Analytics (2014) Global Water Intelligence

[34] Mott MacDonald water industry experience

benefits may be derived from combining both sources of information, as well as that from other monitoring technologies such as fast logging (to improve understanding of consumption and distinguish between customer night use and leakage) and pressure sensors (because pressure management is a key component of most companies' leakage control programmes).

In addition to increasing use of sensors in the network, remote monitoring using imagery from satellite and aerial technologies (including unmanned aerial vehicles) is currently being piloted by at least six UK water companies (Appendix A) and could provide complementary information on a wider geographical scale, particularly in lower density areas where the cost of installing sensors on the network may remain prohibitive in the short to medium term.

The resulting improved understanding of background leakage, from combining information from these and other data sources, could help improve asset management through better targeting of water mains renewal. This is a highly capital-intensive activity with Thames Water, for example, investing approximately £850M between 2005-10 in its Victorian Mains Renewal programme to replace 1868km of mains to reduce leakage in London[35]. Improved targeting of mains renewal based upon long-term monitoring data therefore presents significant opportunities for cost efficiency where water companies are investing heavily to improve asset health of ageing networks.

3.4.3 Preventing critical asset failure

The cost of critical asset failure is high in direct financial and wider economic terms, including the cost of emergency repair, compensation for damage to homes and businesses, traffic disruption, and customers' temporary loss of water supply. Smart monitoring technologies can provide higher quality and faster data enabling earlier detection and prediction of problems. This facilitates timely, proactive asset management investment to intervene before asset failure occurs – typically at lower financial cost, with reduced economic impacts.

The benefit of avoiding a trunk main failure in heavily urbanised areas such as London may already justify the cost of selectively investing in smart monitoring technologies on targeted high-risk parts of the network. Thames Water have committed a £31M investment by 2020 to monitor sections of trunk mains with the highest consequence of failure, increasing coverage from 5% to 8% of their network[36] This will include flow and pressure sensors and acoustic loggers linked to the operational control room to initially provide burst and leak alarms.

The information collected will also inform deterioration modelling and research to understand causal factors for trunk main failure. It is anticipated that this will lead to improved asset management and future cost efficiencies through more effective targeting of asset renewal investment – a significant opportunity with approximately £250M committed between 2015-2020[37].

3.4.4 Improving information management

Deriving value from data collected by smart monitoring technologies relies upon the ability to process it and combine it with other information such as asset condition and performance information, operational events (e.g. interruptions to supply) and activities (including maintenance and project delivery), customers and wider stakeholders, and geographical constraints (e.g. environment, demographics). Data needs to be of appropriate quality and

[35] Thames Water Utilities Limited & Ofwat (2012) *Thames Water Mains Replacement Programme Independent Review*. Available online

[36] Thames Water (2013) *WI Trunk Mains - Investment Area Document* – as referenced in: Thames Water (2017) Trunk Mains Forensic Review. Available online

[37] Thames Water (2017) *Trunk Mains Strategic Review: Final Report*. Available online

resolution (both geospatially and temporally) for its intended use, with a robust governance framework in place to provide assurance that enables future reuse as different applications emerge.

This presents a significant challenge for many infrastructure owners, including UK water companies, who typically have to manage multiple different legacy systems developed for different functions (e.g. investment planning versus capital delivery versus customer billing) with limited integration, that often hold conflicting and incomplete data. This results in limited visibility and sharing of potentially valuable information between different functions in the same organisation.

Improvements in information management, covering both organisational and technical factors, could therefore unlock further benefit than has been identified here for the individual technology case studies taken in isolation. Many water companies are investing in this area, for example Affinity Water's Situational Awareness tool will combine GIS asset visualisation with live operational and control data, asset management information and future metering data. The information will feed decision support tools and prescriptive analytics for optimisation, enabling rapid operational responses, improved decision making and a reduction in incidents, with an expected payback period of under 3 years. However, the greater challenge may be the change in culture required across the sector to ensure that decisions are driven by that information at all levels of the organisation, and can be made in a timely manner.

4 Other sectors

4.1 Introduction

This section provides a brief review the applicability of monitoring technologies in other infrastructure sectors.

4.2 Power Networks

A detailed description of the composition of the Power Networks infrastructure and markets is proved in Appendix F.

4.2.1 Business cases which are proving successful

LIDAR surveys
A number of network operators are beginning to commission full surveys of their overhead line assets, particularly as the technology for Light Detection and Ranging (LiDAR) has been deployed on fixed-wing aircrafts and helicopters. This is delivering benefits in terms of avoided manual inspections which are time-consuming to carry out and arrange, particularly where they require access across farmland. We estimate that the business case is positive over a period of less than 5-8 years, but not a great deal less than this. Scottish Power Energy Networks made an application for to Ofgem via a regulatory mechanism (the "Innovation Roll-Out Mechanism") which is only relevant if the business case is fragile on the 6-year timeframe remaining in the regulatory price-control period.

On-line condition monitoring
The distribution networks are now reporting their productivity in asset replacement and refurbishment using a common asset health score, known as the "Common Network Asset Indices Methodology". This provides a financial mechanism at the level of their whole asset base, with an incentive to improve the health score of the asset base. Within this, network operators can select to deploy online monitoring as a legitimate means to improve the health of an existing asset: since the additional information, and the ability to react to issues in a short timeframe, allow the risk of failure to be reduced to a level of a healthier asset. The assets most suited to online monitoring appear to be transformers.

Automation at high voltages (11kV and above)
The networks have been retro-fitted with high levels of automation down to the 11kV voltage level. These have been driven by a desire to reduce the impact of equipment faults by reducing the number of customers which can be affected. If, following a short interruption, between one-half and two-thirds of customers can be re-supplied automatically by an alternative route through the network, the benefits are significant.

The roll-out of smart meters at domestic premises has not been predicated on supply interruptions, though there are benefits in being able to:

- Identify faults sooner which would otherwise need to be manually triaged through a call centre and associated to a single common fault.
- Identify faults specific to a single customer and caused not by the network but by their own equipment.
- Verify that supply has been restored to isolated or remote premises after major storm events.

4.2.2 Business cases which are not justifying large roll-outs

Low voltage automation
The business case for low voltage automation does not currently warrant large-scale roll-outs within the current incentive mechanisms and the current level of penalties for interruptions. This is partially due to smaller numbers of customers being affected per fault, and partially due to the availability of generation. Nevertheless, the ability of Smart Monitoring and automation to also support balancing of load and to support increasing loads expected from Electric Vehicles and heat pumps has the potential to deliver benefits.

Using immersive technologies during inspection
There are particular assets which may be shared use (for example cable tunnels shared by all of power transmission, telecoms, and gas) where the consequences of a failure have multiple impacts; or dedicated power assets where access is difficult and controlled by another party. In these cases, there is a strong case to carry out immersive and invasive inspection as soon as access to the site can be achieved. There is not currently a proven business case, partly due to the cost of the equipment or the service, and partly due to the fact that the probability of failure is extremely low.

Manual search
There are a number of equipment fault types which, following failure, have to be pinpointed in a manual fashion. Examples occur on both fluid-filled cables for power distribution, on distribution overhead lines, and low voltage cables, where a fault is typically found by splitting the affected cable into two sections, and determining whether the fault is on the upper half or the lower half; and then splitting again into half; and so on until a small enough section has been isolated to be practical to investigate. As stated above, the challenges either come from the lengths of circuits or from the cost and disruption of digging down and failing to find the fault.

Limited roll-outs are being carried out, for example, chemical tracers in the fluid; and Fault Passage Indicators (FPIs) with radiocommunications. These business cases may look different when observed through a lens of wider economic costs of disruption, and job creation in the GB technology supply chain.

A practical way forward would be to gather the network operators' view of target unit price at which the solution would become economic under existing regulation, and to direct existing government R&D expenditure to reach this target price.

Inaccurate location of faults and uncertainty in fault reports
There are promising but nascent technologies such as partial discharge monitoring, which is able to detect faults in certain types of cable by detecting the tiny flash-overs or "discharges" which take place in the insulation of cables which have moved or shifted or degraded. A key challenge for partial discharge is to detect issues within a cable whilst only being able to monitor the remote end or source end of the cable. The technical challenge may be significantly easier if monitoring could take place at several locations on the cable where substations are fitted, but costs to date have been prohibitive. Once again, the approach of articulating a target unit cost and target reliability of a wide-spread deployment at substations may bring forward new innovation, if R&D support is provided.

4.3 Light Rail

Our Light Rail systems share many similar characteristics with the GB heavy rail network which is a key focus of this study. This is particularly true of the London Underground network which has a number of similar asset types and operating systems.

System failures, in particular, related to points and other track assets, occur regularly. Whilst the geographically concentrated nature of the network in London means that system failures can often be resolved quickly, the high volumes of passenger usage suggests that these disruptions have a substantial economic cost.

We therefore expect that installation of monitoring technologies on the UK light rail network, and in particular London Underground, is likely to generate a sizeable additional benefit to the figures estimated for the heavy rail network.

4.4 Highways

The highway network shares a number of similar types of structures to the rail sector, in particular bridges and retaining walls.

There are therefore useful applications for rail structures monitoring technology which could transfer to the highway network.

Structural health monitoring of bridges is an obvious example of this, and has already been implemented successfully at locations such as in Hertfordshire on the M25. Defects were observed in this viaduct and monitoring was installed to understand the performance of the asset given traffic loads, and to determine the most efficient remedial strengthening measures. A coordinated investigation into this technology between Network Rail and Highways England, may be one way to improve the understanding of the potential benefits, and to stimulate a reduction in technology costs.

Monitoring technologies to avoid rail bridge strikes would also be of benefit to the highway sector and in particular local highway authorities. Monitoring at key strategic locations linked to safety systems in autonomous vehicles may be a cost-effective way to improve safety on highway networks.

Finally, investment in monitoring technology to avoid or mitigate rail network disruption will benefit users of the highway network through an avoided modal transfer to private car travel. The externalities of car travel such as road traffic congestion, accidents and local air pollution are monetised as standard in DfT (and therefore HMT) investment appraisal methodology.

5 Conclusions and recommendations

5.1 Study conclusions

Smart monitoring can deliver significant returns on investment, particularly when targeted carefully

Our work suggests that even basic monitoring technology could generate substantial returns if targeted in the right areas. Existing technology to mitigate the disruption to rail services from a road vehicle strike could pay back almost immediately on the highest value and most susceptible bridges, generating cost savings in excess of £3 for every £1 spent in installing and operating the system.

Our analysis indicates that investments in water smart metering or permanent acoustic logging could each generate returns of over £2 for every £1 spent, for those companies with the highest marginal cost of supply – typically in water stressed regions.

Network Rail has supplied an early draft of its Intelligent Infrastructure Strategic Plan for 2019-2024. This suggests that an investment of circa £380M between 2019 and 2024 could generate over the same period a gross saving of £670M and a net saving of £290M. This level of return is broadly reflective of our related case studies. The net saving for year five of this plan is circa £200M per year. We expect that this will become an ongoing annual saving as the bulk of the initial investment will have taken place, although broadly half of the investment is contingent upon future business case development, so the savings may be lower and/or take longer to occur.

It important to emphasise that this is from an early draft of Network Rail's plan, and the figures may change. The specifics of this plan which have been shared with us suggest that the shorter-term applications of smart infrastructure including monitoring technologies which would contribute to this saving, relate mainly to components in the rail system which fail frequently, such as points and track circuits. These technologies have not been the focus of our case studies.

In certain circumstances water companies could benefit from positive returns on investment from the monitoring technologies analysed in this study. Allowing for future technology cost reductions, smart metering could offer a total lifetime net saving of £600M to £1.5bn, and permanent acoustic logging a saving of £100M, if deployed nationally by all companies with a positive net present value. In both cases the savings are based upon analysis of pilot-scale deployment of the smart monitoring technologies, with significant uncertainty in how the costs and benefits may transfer to national scale.

Each water company operates in a unique context, resulting from the combination of factors such as level of water stress, per capita consumption, leakage performance, age and health of assets and existing meter coverage. As a result, there is significant variation between companies in return on investment for the smart monitoring technologies considered here.

As both technologies considered in the CBA relate to water efficiency, the best returns will be limited to those companies with the highest cost of water supply. As bulk supply options are developed, enabling transfer of water resources between companies, this discrepancy would reduce. Monitoring technologies that do not deliver significant water saving benefits (such as process treatment optimisation) may be expected to vary less between companies, and therefore offer greater opportunities to establish the necessary economies of scale to drive cost reductions through implementation nationally.

Reducing the level and impact of asset failure is a key priority

This is particularly the case for the rail sector, where disruption to services results in wasted time and dissuades the people affected from travelling in the future.

We have produced a high-level estimate of the potential longer term total financial and economic cost of disruption which could be saved through monitoring technologies. This is to demonstrate that there is substantial long-term value of these technologies. Our estimate is a reduction in the financial and economic cost of rail disruptions by around £0.6bn per year, split £0.16bn through increased rail fares revenue, and £0.44bn through travel time savings and other wider impacts. These figures are gross savings as they do not include the up front or ongoing costs of monitoring.

The installation of similar technologies on the UK light rail network, and in particular London Underground, is likely to generate substantial further benefits.

For some technology the returns are potentially huge, but currently unproven

The impacts of major rail asset failures such as the collapse of a viaduct or a retaining wall can extend to tens or even hundreds of millions of pounds per incident and the use of monitoring technology to provide early warning of these total asset failures can deliver a substantial potential financial and economic prize. There are also potentially significant safety benefits from removing or reducing the need for human inspections.

These financial, economic and safety benefits apply across all transport sectors. There are few current field trials of this application of monitoring technology and therefore we see benefit in investment in pilot studies to establish the value in this context.

There is a similar role for monitoring technology in the water sector to avoid critical asset failure such as trunk main bursts, which can cause significant disruption to communities and transport networks. Water companies are beginning to invest in this application of monitoring technology, and the information collected from these early deployments will be used to develop techniques to predict and prevent asset failure, central to the business case for investment.

A clear application of monitoring technology is to defer and/or optimise asset renewals and the provision of new capacity. Deferral of rail bridge structures renewals may be required as the current Victorian asset base continues to age, however use of smart monitoring is only likely to have a financial payback if current costs reduce by around 25%.

The appropriate scale of a financially viable technology rollout will depend on future cost reductions

The newer and more innovative applications of monitoring technology are currently expensive.

In the limited structural health monitoring trials on rail bridges, the installation costs alone were in the tens of thousands per bridge, with ongoing data capture and monitoring additional to this. The installation cost of smart metering for water is currently over £300 per property, including the cost of the private telecoms network required.

These costs are driven by the limited scale of the current technology and the need for investment in digital infrastructure to collect, transfer and manage the data. Alternative scenarios that consider national deployment of current technology, or the use of future networks designed for the Internet of Things could provide significant cost reductions and potentially positive returns on investment. Such a scenario could make the economic benefits outweigh the costs of smart metering for all water companies.

A wide range of benefit to cost ratios are possible for the different water companies across the three smart metering scenarios considered, from £0.50p to £2.70 per £1 spent. Achieving the higher end of that range, with payback periods as short as seven years depends upon reductions in technology cost – for example through national deployment of current technology or delaying implementation by five years to 2025 to use future networks designed for the Internet of Things (e.g. 5G). Greater benefit may also be achieved through higher water savings from improved customer engagement and demand-based tariffs reducing consumption and enabling further investment deferral, and improved targeting of leakage detection using the information available from smart meters. Such a scenario would make the economic benefits outweigh the costs of smart metering for all 12 companies considered in this analysis.

There are challenges to realising the full benefits of smart monitoring

Given sizeable initial outlays and the ongoing nature of the benefits, mass adoption of smart monitoring technology is unlikely to generate a positive financial return for several years. Technology cost reductions are required, but the scale of opportunities with attractive returns on investment – particularly in the context of five-year regulatory cycles, may not be sufficient to drive down costs and alternative sources of pump priming funding may also be required.

The economic benefits of smart monitoring technologies do not always translate into direct financial savings for infrastructure companies. In the case of Network Rail, economic impacts such as travel time savings account for 70% of the total benefit, and for water smart metering that ratio is typically over 50%, consisting of energy hot water savings and reductions in home insurance premiums. This highlights the importance of regulatory mechanisms, such as outcome delivery incentives in the water sector, to encourage companies to invest where there are economic benefits beyond the cost savings. An example of these wider benefits is a reduction in externalities, such as air pollution, associated with lower energy consumption to heat water.

Asset managers are not always incentivised to collaborate with other organisations or to share information and innovations, particularly in a competitive environment. This is a barrier to understanding the full potential of data-driven technologies and to achieving cost reductions through better market knowledge and the economies of scale possible from mass adoption.

There are wider opportunities from smart infrastructure

This study has focussed on a limited number of specific technology case studies, and a comparison of our results with the wider portfolio of evidence.

The largest benefits are likely to be obtained from combining data from multiple monitoring technologies, enabled by investments to improve asset information, data management and other components of smart infrastructure systems such as decision support tools and prescriptive analytics. Equally important are changes to asset management and operational procedures to ensure maximum value is derived from the available information. It has not been possible to quantify and allocate these benefits to any single technology case study in isolation, however, ongoing trials such as the Smart Water Networks for Europe project which integrates interventions across four separate areas, could provide further insight. The Smart Water Networks Forum estimates the full potential value of smart water infrastructure at £2.7bn per year across European utilities.

The greatest unquantified opportunity is from the value of information being shared across multiple sectors, improving productivity across infrastructure and construction as part of a 'system of systems' National Digital Twin. This could deliver efficiencies at strategic, tactical, and operational levels through improved coordination between different infrastructure owners, as well as wider value from the availability of open data sources to deliver better public services.

5.2 Study recommendations

We have the following key recommendations:

1. There is a clear financial and economic case for targeted investment in certain monitoring technologies. Infrastructure asset owners should evaluate these opportunities and ensure appropriate investment is built into future plans.
2. The benefits of using monitoring technologies to avoid critical asset failures are potentially considerable, but the business cases are largely unproven. Further work is required to develop techniques that detect early warning signs and provide sufficient time to take action to prevent critical asset failure. This should include technology trials to evaluate and demonstrate the business case for specific applications, such as proactive structural health monitoring in the rail sector.
3. Slow financial paybacks can be a barrier to investment in monitoring technologies, despite the potential economic benefits. Further review is required to determine whether the necessary market conditions exist to encourage infrastructure owners to invest where there is a strong economic case to do so, or if further incentives may be required.
4. Infrastructure owners should invest in improving information management and supporting systems to be able to obtain the full benefit of smart monitoring technologies. A national information framework that ensures consistency and compatibility between different sectors and organisations would enable further future benefits in the form of a 'system of systems' National Digital Twin.
5. Future networks designed for the Internet of Things, including 5G, are a key enabler for widespread adoption of smart monitoring technologies. Delivering that ubiquitous connectivity is a priority to drive down costs and unlock further investment in smart monitoring technologies.
6. Further work is required to assess a wider range of smart monitoring applications, particularly opportunities in water non-infrastructure (i.e. treatment works) and wastewater. The findings of this study should be reassessed once draft WRMP19 plans are available from water companies, and Network Rail issues its Intelligent Infrastructure Strategic Plan for 2019-2024.
7. A comprehensive portfolio of data from technology trials and studies of the type undertaken at Marsh Lane viaduct would be beneficial, and it is recommended that a separate, more detailed, and wide-ranging study is undertaken to more confidently establish a business case for technologies and scenarios with the greatest potential. It is also recommended that the opportunities smart monitoring can potentially offer in relation to the deferral or reduction in rail structures renewals is considered as part of a future detailed study.

Appendices

A. Water Sector Case Studies: Long List

Digital monitoring technology R&D and innovation projects

Organisation	Project title
Affinity Water	Detecting leakage using satellite imagery
Affinity Water	Fast logging for improved measurement of leakage
Anglian Water	Aerial technologies to detect leakage
Anglian Water	Managing leakage and transients
Anglian Water	SMART Metering
Anglian Water	Real time control of sewers
Anglian Water	Real time control water networks
Northumbrian Water	Asset management - condition assessment, leakage
Scottish Water	Prediction and control of Discolouration in Distribution Systems Implementation
Scottish Water	Variable Consenting of Wastewater Treatment Works
SES Water	Enhanced leak correlation
SES Water	Leak detection using drones
SES Water	Remote main condition assessment
SES Water	Smart Metering
SES Water	Smart Networks
SES Water	Smart valves
Severn Trent Water	Hawkeye level monitors on wastewater network
South West Water	Supply interruption dataloggers
South West Water	Condition-based maintenance of pressure management valves
South West Water	Advanced pressure management valve controllers
South West Water	Dynamic hydraulic models
Southern Water	Aerial Technologies for leakage detection
Southern Water	Water site optimisation
Southern Water	Waste water site optimisation
Southern Water	Smart Meter trials
Southern Water	Sewer monitoring
Southern Water	Asset status analysis
Thames Water	Leak Detection Innovations
Thames Water	Unaccounted for water
Thames Water	Smart meter trial

Organisation	Project title
Thames Water	Trunk Main Research
Thames Water	Weather Impact on Operations
Thames Water	Risk and Performance Monitoring
Thames Water	Data Driven Water Production Insight
Thames Water	Buried Asset Knowledge Enhancement
Thames Water	Infiltration Detection and Solutions
Thames Water	Real Time Control for integrated catchment management
Thames Water	Smart Water 4 Europe
Thames Water	Customer sewer alarms for blockage early warning
Thames Water	Sewerbat acoustic sensing technology for rapid initial survey of sewers
Thames Water	SOLO unmanned robotic inspection of small diameter sewers
Thames Water	Multispectral inspection of large diameter sewers
United Utilities	Water leakage
United Utilities	Systems thinking
United Utilities	Wastewater network innovations
United Utilities	Smart networks
United Utilities	Unmanned vehicles / automation
United Utilities	Wastewater process optimisation
Dwr Cymru Welsh Water	Fast logging trial
Yorkshire Water	Fibre optics in water mains
Yorkshire Water	Smart Waste Networks
Yorkshire Water	Smart Water Networks
MML - Low Carbon Study	Smart waste water meters
MML - Low Carbon Study	iNet - i2O smart network solutions
MML - Low Carbon Study	GRID Optimiser (pump optimisation)
MML - Low Carbon Study	ElectroScan for infiltration detection
MML - Low Carbon Study	Temperature Loggers for infiltration detection
MML - Low Carbon Study	Distributed Temperature Sensing for infiltration detection

Source: UKWP (2017) LITSoN Pilot Database and Mott MacDonald analysis

Possible data sources for shortlisted case studies

	1 Smart metering	2 Water network sensors	3 Smart wastewater network	4 Wastewater process optimisation
Anglian Water	X		X	
Southern Water	X		X	X
Thames Water	X	X	X	X
Affinity Water		X		
Yorkshire Water			X	
Severn Trent Water		X	X	
Dwr Cymru Welsh Water		X		
United Utilities		X	X	

Source: UKWP (2017) LITSoN Pilot Database and Mott MacDonald analysis

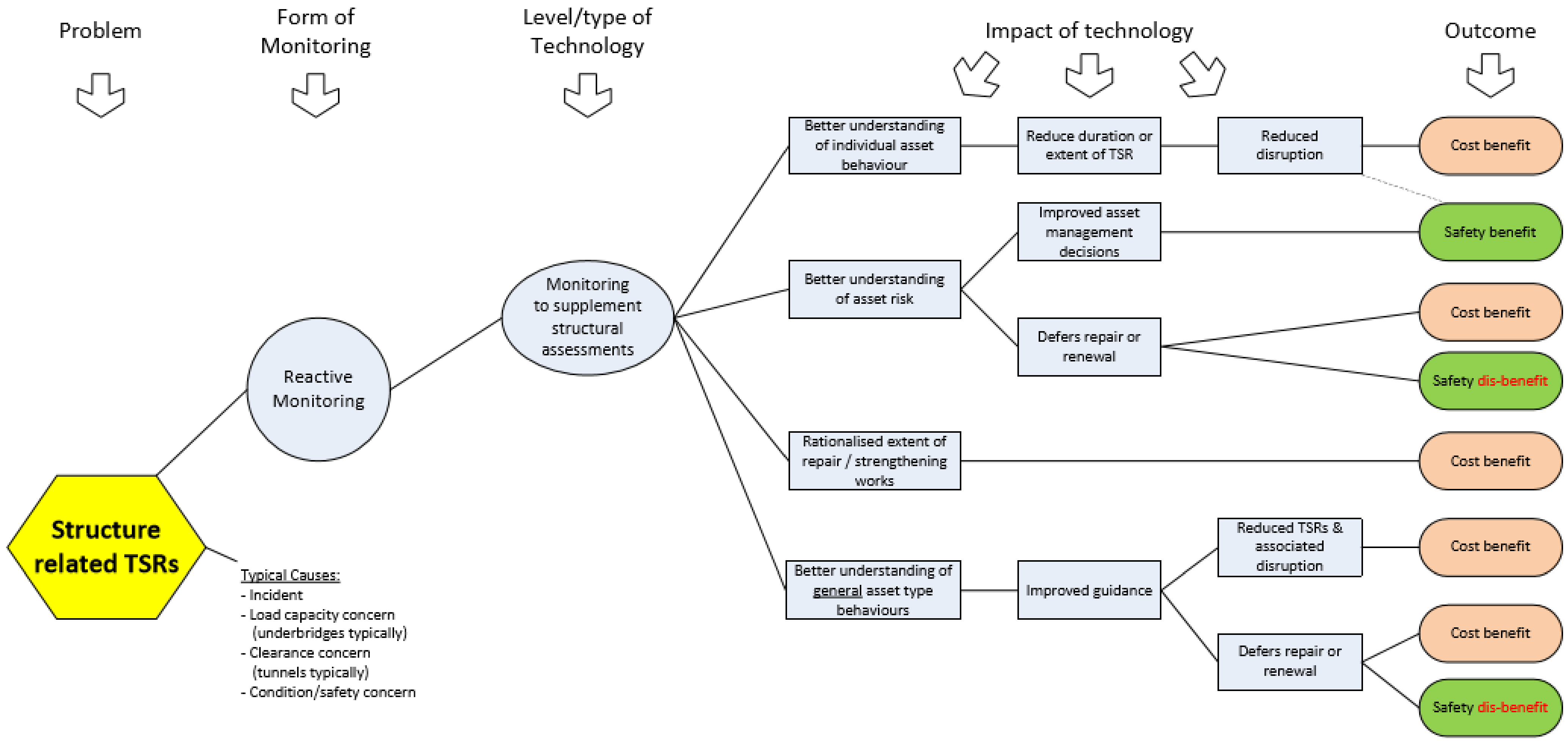
B. Case Studies Short List: benefit maps

This appendix contains benefits maps for the following case studies:

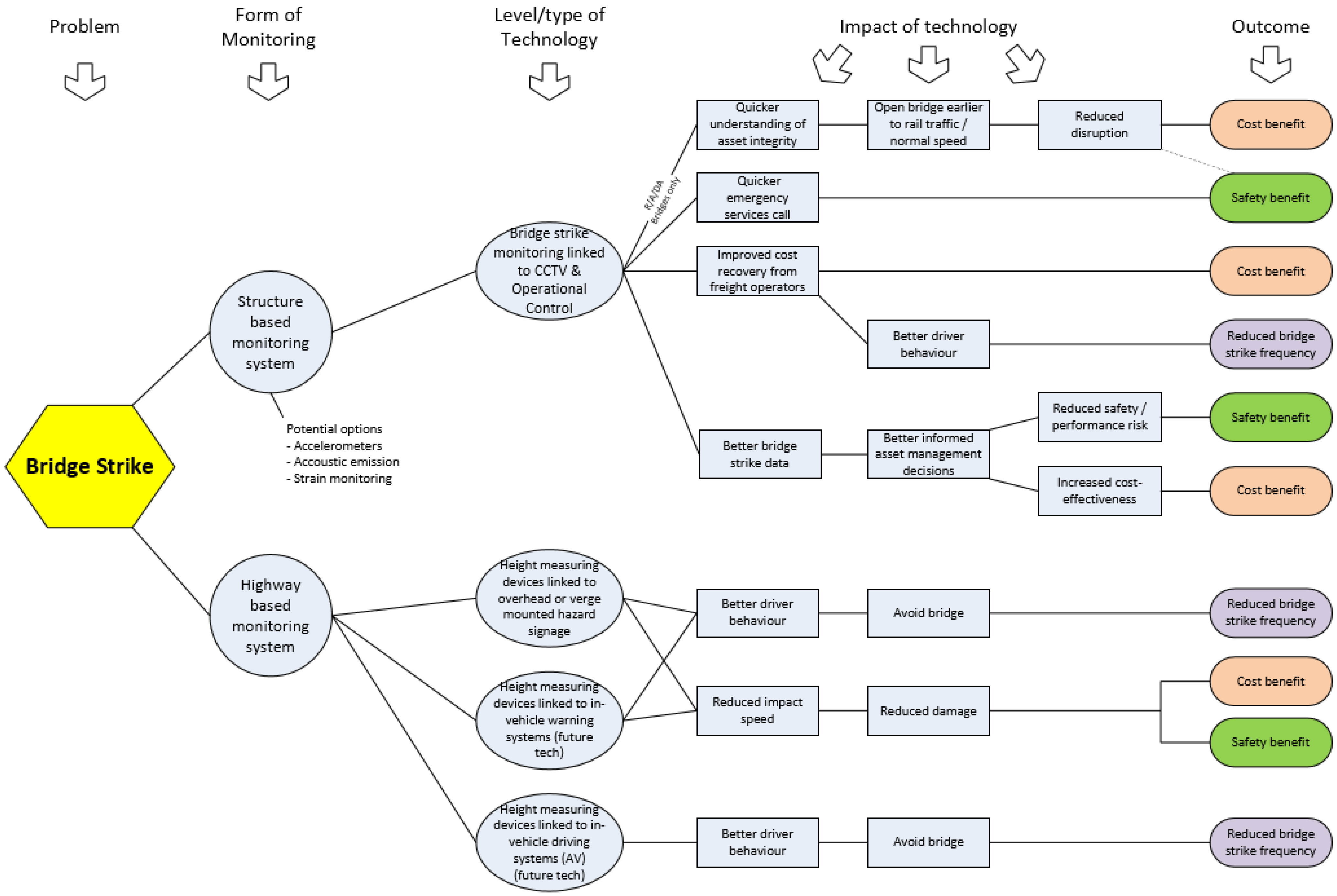
- Rail – Structure related Temporary Speed Restrictions
- Rail - Bridge strikes
- Water – Smart metering
- Water – Permanent acoustic logging

A benefits map for the rail renewals deferral case study has not been produced as the benefit is a simple push back of renewals expenditure.

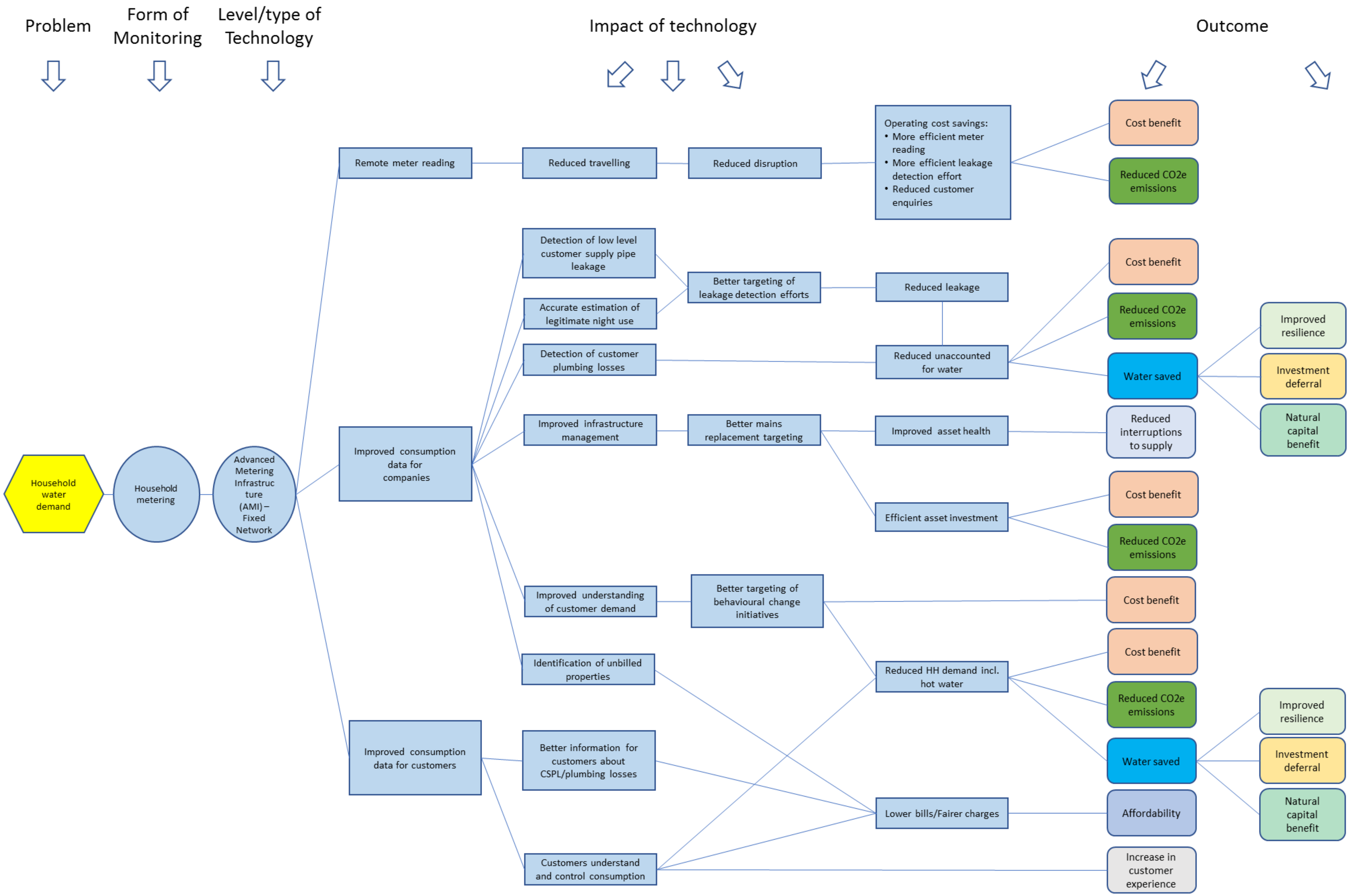
B.1 Rail – Structure Related Temporary Speed Restrictions (for example Marsh Lane viaduct)



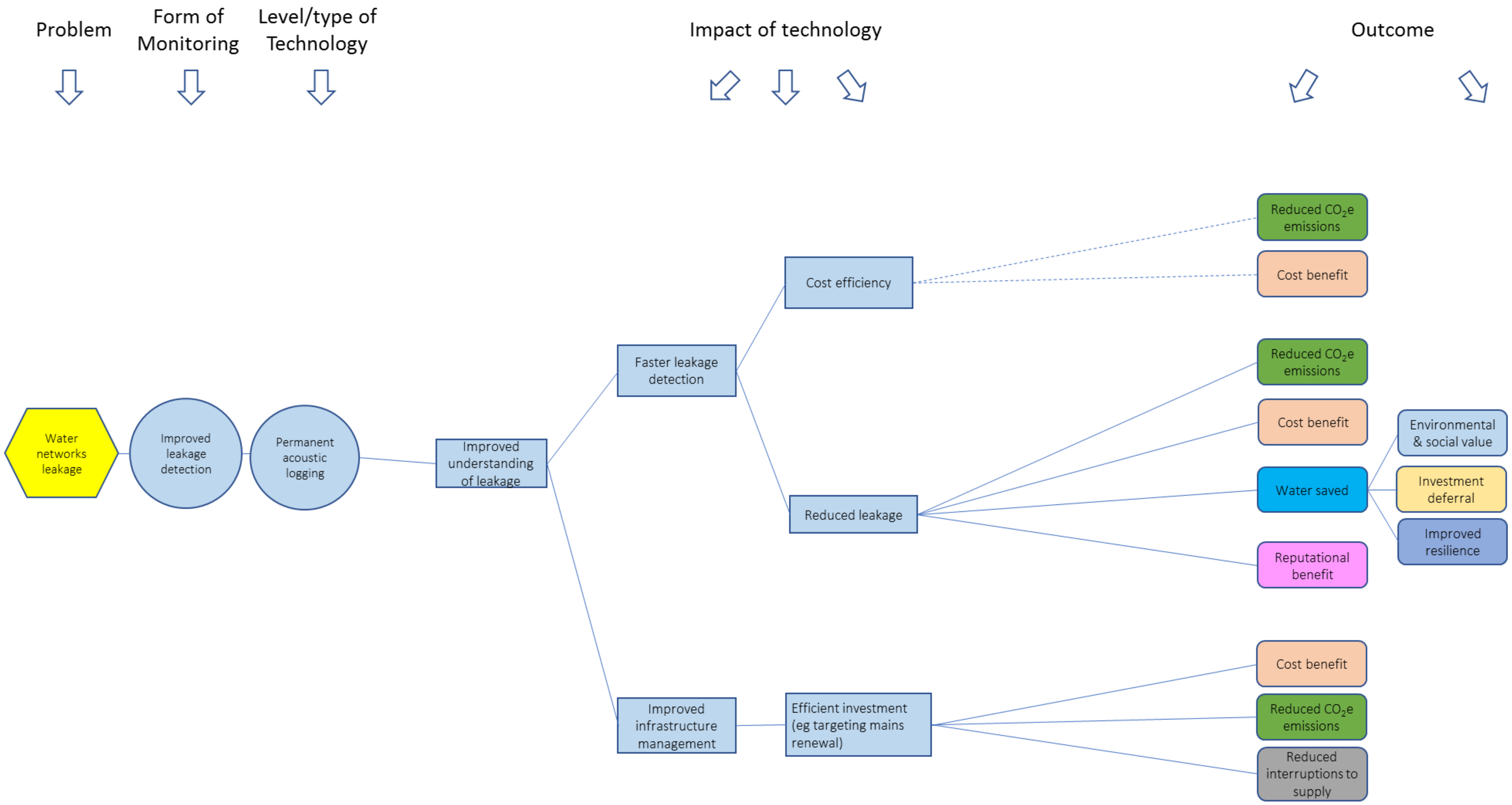
B.2 Rail – Bridge Strikes



B.3 Water – smart metering



B.4 Water – permanent acoustic logging



C. Rail structures asset restrictions

Table 6 shows a list of safety related incidents on rail structures which could potentially be avoided by monitoring technologies

Table 6: Safety related incidents on rail structures which could be potentially avoided by monitoring technologies

Root Cause	% of Safety Incidences	Monitoring
Emerging defects not identified at Visual Exam	11.63%	Proactive
Unknown	11.63%	Proactive
Failure/lack of water control	9.10%	Reactive
Poor design	6.32%	Reactive
Poor maintenance	5.31%	Reactive
Recommendations raised but risk scored too low	4.55%	Proactive
Lack of asset knowledge	4.30%	Proactive
Defect not recorded at Detailed Exam	3.92%	Proactive
Poor workmanship	3.79%	Reactive
Damage due to construction or maintenance activities	3.67%	Reactive
Proposed intervention correct but specified timescale too long	3.41%	No
Defect identified at DE but had already deteriorated such that UDR required	2.53%	Proactive
Weather related - Freeze/Thaw	2.53%	Proactive
Defects identified in either Visual or Detailed Examination but no recommendation raised	2.40%	Proactive
Weather related - Flooding	2.28%	Proactive
Overloading	2.15%	Proactive
Poor vegetation control	2.02%	Proactive
Weather Related - Storm Surge/Wave Action	1.90%	Proactive
Work item raise but works not carried out	1.64%	Proactive
Weather related - Heavy Rain Event	1.39%	Proactive
Failure to identify site risk	1.26%	Proactive
Railway crime	1.26%	Proactive
Recommendation raised, risk scored correctly but rejected	1.01%	Reactive
Construction works not carried out to specification, poor onsite test & inspection	0.88%	Reactive
Failure to Implement mitigation measures to provide robustness	0.88%	Proactive
Failure to provide adequate ballast retention	0.88%	No
Works prioritised correctly but not undertaken within specified timescales	0.76%	No
Defect identified at Visual Exam but had already deteriorated such that UDR required	0.63%	Proactive
Weather related - Ice/Snow	0.63%	Proactive
Weather related - Wind	0.63%	Proactive
Failure to Implement mitigation measures to reduce frequency	0.51%	Reactive
Misuse	0.51%	Proactive

Root Cause	% of Safety Incidences	Monitoring
Road Traffic Incident	0.51%	Reactive
Derailment	0.38%	Reactive
Obstruction on waterway	0.38%	Reactive
Safety risks not fully assessed	0.38%	No
Work planned but delayed	0.38%	Reactive
Failure to identify site risk for potential vehicle incursion	0.25%	No
No failure identified	0.25%	Proactive
Specification insufficient to adequately describe the extent of remediation required	0.25%	No
Structure moving/pumping under load	0.25%	Reactive
Earth slip	0.13%	Reactive
Mortar deterioration	0.13%	Reactive
Recommendation raised, risk scored correctly but reduced in subsequent examination	0.13%	Proactive
Uninhibited chain reaction caused by hot cinders	0.13%	No
Uninhibited chain reaction caused by illegal heater	0.13%	No

D. Study references

Below is a list of our key reference material.

D.1 Rail

https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/220541/green_book_complete.pdf

https://www.gov.uk/guidance/transport-analysis-guidance-webtag

https://www.rssb.co.uk/risk-analysis-and-safety-reporting/risk-analysis/taking-safe-decisions/taking-safe-decisions-safety-related-cba

Network Rail PFPI costs for 2012/13 – 2016/17

Network Rail Schedule 8 payment rates

Network Rail early draft Intelligent Infrastructure Strategic Plan, dated 13th October 2017

Network Rail analysis of Schedule 8 rates compared to Value of Time Savings and non-user impacts

Network Rail standard NR/GN/CIV/202 *'Management of the risk of Bridge Strikes'* (Issue 3)

Network Rail standard NR/L3/CIV/028 *'The management of reports of Safety-Related Events on Buildings and Civil Engineering infrastructure'* (Issue 5)

Network Rail Bridge Strike Database data (2007/08 to 2017/18 Period 6)

Network Rail Buildings and Civils Safety Related Events Register data (2007/08 to 2017/18 Period 6)

Network Rail Civil Asset Register and electronic Reporting System (CARRS) data (October 2017)

Network Rail Train Delay data (2014/15 to 2017/18 Period 7)

Network Rail Regulatory Financial Statement to year end 31/03/2017

Network Rail Strategic Business Plan (CP5) and supporting documents

Network Rail report *'Independent Review of Depreciated Replacement Costs for Engineering'*, by Arup, 2014

CSIC data on the Marsh Lane Viaduct

RSSB Safety Management Intelligence System (SMIS)

RSSB Safety Risk Model (SRM)(v8.1)

RSSB Annual Safety Report

DfT HGV mileage forecasts 2015

DfT Accident and casualty costs (RAS60)

DfT Vehicles involved in reported road accidents (RAS20)

Mott MacDonald Bridge Strike Study undertaken on behalf of Network Rail (2016)

D.2 Water

Accent (2014) Comparative Review of Willingness to Pay Results. As cited in: United Utilities Water (2016) Improving Customer Research and Engagement, p8

Anglian Water confidential information and case study data

Affinity Water confidential information and case study data

BEIS (2017) Green Book supplementary guidance: Valuation of energy use and greenhouse gas

BEIS (2017) Green Book supplementary guidance: Data tables 1-19: LRVC of Energy Supply

Backblaze (2017) Hard drive cost per gigabyte

CNet (2014) Google on cloud storage pricing: 'Follow Moore's Law'

Cave (2009) Independent Review of Competition and Innovation in Water Markets: Final report. DEFRA.

DECC (2013) The Future of Heating

DEFRA (2013) Market Transformation Programme – Policy Energy Consumption

Discover Water: https://discoverwater.co.uk

ICF (2017) Improving willingness-to-pay research in the water sector

Legal & General (2011) Stop the Drop

Media Analytics (2014) Global Water Intelligence

ONS (2016) UK Population Projection: Table A1-1 Principal projection – UK summary

OSISoft (2017) Yorkshire Water case study – SWAN Research

Ofwat (2007) Providing Best Practice Guidance on the Inclusion of Externalities in the ELL Calculation

Ofwat (2013) Setting price controls for 2015-20 – final methodology and expectations for companies' business plans: Appendix 5 Ofwat (2014) Water company final determinations [various]

Ofwat (2014) Water company final determination feeder models [various]

Ofwat (2017) Delivering Water 2020: Consulting on our methodology for the 2019 price review

Ofwat (multiple years) Water company June Returns data

Smart Water for Europe: https://sw4eu.com

Thames Water, Water Resources Management Plan 2019. Demand Management Feasible Options Paper. June 2017

Thames Water (2013) WI Trunk Mains - Investment Area Document – as referenced in: Thames Water (2017) Trunk Mains Forensic Review

Thames Water (2017) Trunk Mains Strategic Review: Final Report

Thames Water Utilities Limited & Ofwat (2012) Thames Water Mains Replacement Programme Independent Review

UKWP (2017) LITSoN Pilot

UKWIR (2012), Smart Metering in the Water Sector Phase 3 - Making the Case (12/CU/02/13)

UKWIR (2011), Long Term Leakage Goals (11/WM/08/44)

Water UK (2016) Water Resources Long-Term Planning Framework

E. Cost Benefit Analysis Methodology

E.1 Background

Our cost benefit analysis was developed in a manner consistent with the HMT Green Book. This appendix provides a summary of method used.

E.2 General assumptions

Our general assumptions are as follows:

- **Appraisal period.** As per the assumed technology asset life.
- **Price base**. 2016/17 prices and values.
- **Annual discount rate**. 3.5% for the years 1-30, 3% for years 31-75.

E.3 Rail sector assumptions

- **Methodology**. Department for Transport WebTAG, consistent with HMT Green Book.
- **Exogenous Rail Demand Changes**. Mott MacDonald forecast, consistent with WebTAG
- **Road Traffic Forecasts**. Department for Transport forecasts
- **Rail fares revenue impact of network disruption per Train Operating Company**. Confidential rail industry payment regime data, supplied by Network Rail.
- **Wider impacts of disruption.** Analysis undertaken by Network Rail and review by Mott MacDonald. – The figures are consistent with WebTAG.

Table 7: Summary of CBA for Bridge Renewals Case Study

Name	Description	Assumptions
Rollout	Strategy for installing monitoring equipment	Monitoring installed on all structures that are due to be renewed the following year (~200 per year).
Renewal expenditure	Annual Network Rail expenditure on structural renewals	Scenario 1 - Future expenditure = 2016/17 expenditure Scenario 2 - Future expenditure as forecast in CP5 plans
Average renewal cost	Average renewal cost per structure	Average replacement cost = £2.8M (ORR report). Average renewal cost = £2.0M (mixture of refurbishment and renewals)
Renewals deferral	Deferral of renewals costs	Base case assumes renewal deferred for 20% of monitored structures with average deferral of five years.
Technology installation	Cost of installing the monitoring and data capture equipment	Average of £50k per installation
Ongoing costs	Cost of the monitoring, data processing and analysis	10% of installation cost per year

Table 8: Summary of CBA for Bridge Strike Case Study CCTV based system

Name	Description	Assumptions
Applicability	Proportion of bridges where the technology could result in a saving	'Red' classified low headroom bridges struck over last ten years (~31% x 2,500 bridges = 618). (Red classified bridges require suspension of rail services until a struck bridge has been examined).
Rollout	Time taken to install the technology across all in scope bridges	Three years (max 300 sites per year)
Ramp up	Time taken for the technology to be used fully as a safety critical system	Three years. Estimate based on complexity of the technology
Benefit per strike	Reduction in delay enabled by the system	30 minutes reduction in delay per strike
Rail fares revenue	Loss in rail fares revenue	Value based upon average 2016/17 PfPI cost per strike from Network Rail Bridge Strike Database
Value of time	Passengers' value of time saved	Calculated using Network Rail multiplier on rail fares revenue
Other impacts	Non-user benefits, typically from a modal transfer from road to rail	Calculated using Network Rail multiplier on rail fares revenue
Technology installation	Cost of installing the monitoring and data capture equipment	Average of £15k per installation
Ongoing costs	Cost of the monitoring, data processing and analysis	Average of £2.5k per installation per year

Table 9: Summary of CBA for Bridge Strike Case Study warning light system

Name	Description	Assumptions
Rollout	Time taken to install the technology	Six years (based upon installation rate of 300 sites per year).
Applicability	Proportion of rail structures where the technology is applied	Monitoring applied to the 2,000 low headroom bridges that have been struck in the last 10 years.
Bridge Strike reduction	Average percentage reduction in number of bridge strikes resulting from technology	40% reduction assumed (ref Network Rail standard NR/GN/CIV/202) I
Rail fares revenue	Loss in rail fares revenue	Value based upon average 2016/17 PfPI cost per strike from Network Rail Bridge Strike Database
Value of time	Passengers' value of time saved	Calculated using Network Rail multiplier on rail fares revenue
Other impacts	Non-user benefits, typically from a modal transfer from road to rail	Calculated using Network Rail multiplier on rail fares revenue
Bridge inspection costs	Avoided inspection engineer costs	£600 per bridge strike
Safety Risk	Railway and highway risks due to Bridge Strike	Upper bound estimate (2.5FWI/yr) based upon evaluation of RSSB and NR data
Vehicle & Goods damage	Reduction in HGV and carried goods damage/repair/replacement costs	Estimate based upon road accident statistics (£18.5k per recorded bridge strike)
Technology installation	Cost of installing the monitoring and data capture equipment	Average of £150k per installation
Ongoing costs	Cost of the monitoring, data processing and analysis	Average of £5k per installation per year

Table 10: Summary of CBA for Bridge Strike Case Study autonomous vehicle system

Name	Description	Assumptions
Rollout	Time taken to install the technology	Assume circa 2030 (future tech)
Ramp up	Time taken for the technology to be used fully as a safety critical system	Assume circa 2030 (future tech)
Applicability	Proportion of rail structures where the technology is applied	All low headroom structures over the public highway would be covered (circa 3,500)
Bridge Strike reduction	Average percentage reduction in number of bridge strikes resulting from technology	95% reduction
Rail fares revenue	Loss in rail fares revenue	Value based upon average 2016/17 PfPI cost per strike from Network Rail Bridge Strike Database
Value of time	Passengers' value of time saved	Calculated using Network Rail multiplier on rail fares revenue
Other impacts	Non-user benefits, typically from a modal transfer from road to rail	Calculated using Network Rail multiplier on rail fares revenue
Bridge inspection costs	Avoided inspection engineer costs	£600 per bridge strike
Safety Risk	Railway and highway risks due to Bridge Strike	Upper bound estimate (2.5FWI/ yr) based upon evaluation of RSSB and NR data
Vehicle & Goods damage	Reduction in HGV and carried goods damage/repair/replacement costs	Estimate based upon road accident statistics (£18.5k per recorded bridge strike)
Technology installation	Cost of installing the monitoring and data capture equipment	Majority of technology and associated development, installation and operational cost anticipated to be provided as part of autonomous vehicle development. Additional technology and associated cost (for bridge strike mitigation) not known but £15k per site assumed.
Ongoing costs	Cost of the monitoring, data processing and analysis	

E.4 Water sector assumptions

- **Methodology.** Water sector impacts based on Ofwat guidance. Transport sector impacts based on WebTAG.
- **Accrual of financial impacts.** Assumed that all financial impacts are passed through to customers. Zero company profit on expenditure was assumed as this is a transfer payment for appraisal purposes.
- **Water companies included.** A subset accounting for over 80% of the population served in England and Wales was taken for the analysis, consisting of:
  - Affinity Water
  - Anglian Water Services
  - Dwr Cymru Welsh Water
  - Northumbrian Water
  - SES Water
  - Severn Trent Water
  - South East Water
  - Southern Water
  - Thames Water
  - United Utilities
  - Yorkshire Water
- Population growth figures were sourced from water companies WRMP14 submissions up to the year 2040 and based on the ONS national population projection post 2040

E.4.1 Water smart metering case study

Table 11: Summary of CBA for water smart metering

Name	Description	Assumptions
Rollout	Duration and timing of implementation	Rollout over 15 years incl. existing meter replacement Start in AMP7 (Scenarios 1 and 2) or AMP8 (Scenario 3)
Meter purchase and installation cost	The cost of purchasing and installing new meters	Typical industry unit costs
Meter replacement cost	The cost of replacing meters	Meter life 15 years Typical industry unit costs
Reading technology and meter reading activity	Cost of meter reading activity including labour, equipment, and private cost of travelling	Assumption based on Anglian Water data
Telecommunication systems	The costs associated with initial roll-out and on-going expenditure for fixed network smart metering	Assumption based on Anglian Water data
Back-office (IT)	Costs associated with back-office systems (which includes the IT systems for data management system) and include a one-off investment in designing and purchasing a new system, and on-going costs	Assumption based on Anglian Water data
Operational and maintenance activity	On-going cost associated with operational activity: • Maintenance of the smart points. • Customer portal and engagement cost	Assumption based on Anglian Water data
Leak investigation costs	The cost of analysing meter data to identify leaks and high users	Assumption based on Anglian Water data
Household leakage repairs	The cost of addressing customer supply pipe leakage and internal plumbing leak repairs, which depending on water company policy may be provided for free, or paid for by the customer	Assumption based on Anglian Water data, taking a weighted average of company-funded, customer-funded and internal repairs.
Customer demand reduction	Volume of water saved from reduced household consumption (including plumbing losses)	Assumption based on Anglian Water draft plan for WRMP19.
Customer side leakage reduction	Volume of water saved from reduced CSPL incl. low level supply pipe leakage	Assumption based on Anglian Water data
Company side leakage reduction	Volume of water saved from reduced network leakage	Assumption based on Anglian Water and Thames Water data
Deferral of supply side investment	Deferred or avoided costs on large scale infrastructure investment	Company-specific costs calculated from marginal AICs committed in WRMP14, based on Water UK report
Deferral of wastewater investment	Deferred or avoided costs on large scale infrastructure investment in sewers and wastewater treatment	Calculation based on the proportion of future growth avoided through PCC reductions, using PR14 final determination feeder models
Customer call reduction	Reduction in customer contact from more accurate billing	Assumption based on UKWIR report
Hot water energy saving	Monetised value of saved energy from water heating in the home. Divided into carbon from gas and the energy costs.	Calculation based on DEFRA Market Transformation Programme, DECC Future of Heating and BEIS Long-Run Variable Costs of Energy Supply
Insurance cost reduction	Home insurance premium reduction from reduced escape of water cost element	Assumption based on insurance industry report 'Stop the Drop' on

Name	Description	Assumptions
		the cost and causes of escape of water claims
Environmental and social benefit	Reduction in mileage travelled for meter reading purposes	Mileage based on Anglian Water data

Table 12: Summary of water smart metering scenarios considered

	Scenario 1	Scenario 2	Scenario 3
Costs			
Meter purchase	£65	Less 5% every 5 years (each AMP)	Less 5% every 5 years (each AMP)
Meter installation (new)	£230	£180	£180
Meter replacement	£50	£35	£35
Reading technology and meter reading activity	Included in telecommunication system cost	Included in telecommunication system cost	£2.50
Telecommunication systems	Supplier quote	Supplier quote less 20%	IoT starting in 2025 therefore no capex cost
Back-office (IT)	£3/property/yr	£1/property/yr	£1/property/yr Less 5% per annum
Benefits			
Customer demand reduction	-3%	-4%	-7.20%
Customer side leakage reduction	Approx. -50% over 25 years	As scenario 1	As scenario 1
Company side leakage reduction	-5%	-8%	-8%
Deferral of supply side investment	Company-specific AICs from WRMP14	As scenario 1	As scenario 1
Customer call reduction	As is	As scenario 1	As scenario 1
Energy and carbon savings from reduction in hot water consumption	Assumes hot water savings proportional to reduction in PCC	As scenario 1	As scenario 1
Insurance cost reduction	£0.79/property/year	As scenario 1	As scenario 1

E.4.2 Permanent acoustic logging case study

Table 13: Summary of CBA for permanent acoustic logging

Name	Description	Assumptions
Rollout	Extent, duration, and timing of implementation.	Loggers deployed in targeted manner to highest leakage parts of network. Exact percentage calculated using ALC curve described below to pro-rata from Affinity Water data. Rollout over 5 years incl. existing meter replacement Start in AMP7 (Scenario 1) or AMP8 (Scenario 2)
Acoustic logger purchase and installation cost	The cost of purchasing and installing new loggers	Assumption based on Affinity Water data
Logger replacement cost	The cost of replacing loggers	Logger life 15 years Assumption based on Affinity Water data
Operational and maintenance activity	On-going cost associated with operational activity: • Maintenance of the loggers – including battery replacement. • Data analytics	• Current 5-year life (supplier HWM guarantee). Assumed to double to 10 years under Scenario 2 using low-power IoT networks (e.g. NB-IoT, LTE-M or 5G) • Assumption based on Affinity Water data – 2 FTE staff. Assumed one extra FTE per 50,000 loggers deployed
Active Leakage Control (ALC) savings	Company-specific ALC budgets and % spend on detection estimated using regression analysis from available industry data, as a function of leakage performance (ℓ/prop/d and m^3/km/d)	Marginal cost of leakage reduction increases with leakage performance following typical power-law SELL curve. ALC efficiency taken as 80% of saving reported by Affinity Water trial – to allow for
Benefits of proactive not reactive leak repairs	Reduction in operational cost and economic disruption from enhanced detection increasing proportion of proactive leak repairs	Assumed 10% of repairs change from reactive to proactive repairs. Assumed 30% reduction in time required for reactive repair, compared to proactive repair Repair costs taken from typical water company data Assumed 80% repairs cause delay to traffic
Company side leakage reduction	Volume of water saved from faster detection of leaks	Assumption based on Affinity Water data
Customer call reduction	Reduction in customer contact from more accurate billing	Cost assumed based on UKWIR report. Assumed 1.5 calls per leak

F. Stakeholder Workshops

F.1 Background

Two workshops were held on 1st November 2017. The workshops were attended by stakeholders from the water and the rail sectors respectively. The purpose of the workshops was to present our analysis and our emerging findings to the various stakeholders, in particular, to enable scrutiny of our work and an informed discussion on the key issues.

Both workshops were productive forums and substantive feedback was received, as well as offers of further data to support our analysis.

F.2 Water sector workshop

A list of attendees at the water sector workshop is provided in Table 14.

Table 14: Water sector workshop attendees

Name	Organisation
Sarah Hayes	NIC
Andrew McMunnigall	NIC
Aleister Hellier	NIC
Will McGeehin	NIC
Arnaud David	Affinity Water
Doug Spencer	Anglian Water
Jeremy Heath	SES Water
Emma Ferguson-Gould	Turner & Townsend
Ania Bujnowicz	Mott MacDonald
Sarah Watson	Mott MacDonald
Jamie Radford	Mott MacDonald
Andrew Gordon	Mott MacDonald
Chris Judge	Mott MacDonald

F.3 Rail sector workshop

A list of attendees at the rail sector workshop is provided in Table 15.

Table 15: Rail sector workshop attendees

Name	Organisation
Sarah Hayes	NIC
Andrew McMunnigall	NIC
Will McGeehin	NIC
Jennifer Schooling	University of Cambridge CSIC
James Angus	Network Rail
Robert Dean (by telephone)	Network Rail
David Rourke	Network Rail
Simon Ellis	Mott MacDonald
Leo McKibbins	Mott MacDonald
Michael de Voil	Mott MacDonald
Jack Hunter	Mott MacDonald
Eleftherios Stavrakas	Mott MacDonald

Name	Organisation
Warren Bradley	Mott MacDonald
Shane Browne	Mott MacDonald
Andrew Gordon	Mott MacDonald
Chris Judge	Mott MacDonald

G. Power Networks: more detailed context

G.1.1 Overview

Great Britain's electricity sector is an example of an unbundled structure, with separation between electricity supply to end customers, electricity generation, and the transport network (both distribution and transmission networks). Distribution and transmission networks are regulated regional monopolies. The electricity distribution network within England and Wales is separated into twelve license areas, covering a network which interfaces to the electricity transmission network assets at voltages of 66kV or 132kV. The electricity distribution network in Scotland is separated into two license areas, covering a network which interfaces to electricity transmission network assets at 33kV. The remaining distribution networks in the United Kingdom (in Northern Ireland) and the distribution networks in Ireland are regulated under separate arrangements.

The regional monopolies in Great Britain are administered by the Office of Gas and Electricity Markets (Ofgem) which awards licenses, monitors compliance with the license, determines the amount which licensees may charge for regulated activities, and determines boundaries and limits on unregulated activities. The total of fourteen electricity distribution licenses and three transmission licences are currently operated by seven companies, each company operating between one and four regional licenses. The companies propose plans to the economic regulator Ofgem for operating periods of 8 years at a time, known as "price control" periods.

G.2 Commonalities with water and rail

The concept of wider economic loss is the same in electricity as in water and rail - clearly domestic consumers, business consumers and generators of electricity are all affected by power cuts and may incur costs of disruption, damage to property (the contents of their freezer defrosting) and lost income. Ofgem provides a cost-benefit framework in which individual "smart" interventions can be justified on the basis of protecting revenue which generators would lose, since increasingly this has a twin-goal of supporting renewable generation. Individual interventions can also be justified on the basis of the penalties applied to interruptions, safety, and environmental benefits.

The cost of additional resilience, and the level at which the penalties are set for supply interruptions, is reflected through stakeholder consultation at the time of each price control. Individual network operators are required to consult their users and stakeholders and test a "willingness to pay" for levels of resilience.

There are strong commonalities with the water industry in terms of buried assets, where the cost of civil works to dig down to a cable and the cost of re-instatement works to make good dominates repair activities. As such, it is challenging to "retro-fit" solutions to monitor buried cables and solutions are limited to what can be achieved at either end of the cable or at connecting points into the cable.

There are strong commonalities with the water industry and rail industry in terms of sheer network length. This has both a positive impact on the case for Smart Monitoring (since inspection spend is significant) but a negative impact since the up-front capital costs of monitoring can be prohibitive if rolled out to even a proportion of the network.

G.3 Differences with water and rail

The electricity sector is similarly exposed to third party impacts. Whilst in rail these take the form of bridge strikes, the only equivalent taking place with such as similar frequency are strikes to buried cables. These do not have the same impact on supplies as the equivalent bridge strike in rail. On the distribution networks closest to consumers the convention is to restore supplies with temporary generation. The use of temporary generation is already economic under the existing supply interruption penalties.

On the higher voltage circuits of the distribution networks and the transmission networks, significant levels of resilience and redundancy are built in by design. These are enforced by the Transmission Code and Distribution Code approved by Ofgem and involve the ability to supply full load following the first fault, and in some cases following both the first fault and subsequent faults.

This reduces significant outage events caused by asset failure to the order of once in five year occurrences.

The electricity network is more greatly exposed to storm and flood events than is the case in rail or water - since the majority of the electricity network relies on overhead lines to deliver it, whereas this is a "design choice" in rail and catenary supplies are not used throughout the rail network.

The electricity network does not have an immediate analogy with leakages. Whilst the analogy with losses incurred in transmission is tempting, it is not accurate, since technical losses in transmission lines and cables can be reduced but never fully avoided.

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