Working Paper Series

08/2007

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Probabilistic CBA assessment of the CMI SMART Sensor System Project

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Abstract

SMART Infrastructure is an innovative sensor system that provides real-time wireless information about the state of critical infrastructure, which is developed as a part of the Cambridge MIT projects. The SMART sensors are designed to monitor aging infrastructure, such as tunnels and pipelines, as well as to increase capabilities of infrastructure for efficient maintenance. This paper presents the model that assesses the impacts of this new technology, and the findings to date. The probabilistic cost benefit analysis, which takes into account of the future uncertainty, is conducted using the Monte Carlo simulation technique.

The model findings suggest that if the SMART sensor system is applied to the water pipelines in the UK market, huge benefits of avoiding disruption damage costs of water pipe burst as well as reduced annual operation & maintenance costs. The main advantage of this project is that relatively low development and harmonization costs are required despite its large expected benefits. The 5th percentile, mean and the 95th percentile of the cumulative NPV for the UK water pipe market at the year 2056 are US$6, 23.7, and 56.2 billion respectively. The sensitivity analysis indicates that the base year disruption damage cost, the maximum target market penetration rate as well as the discount rate are likely to have significant impacts on the cumulative NPV. The extended model results show that if the STAMRT sensors are introduced to the UK tunnel industry and globally to all the possible industries including bridges and others, base year disruption damage costs and the maximum target market penetration rate have again the most significant impacts on the cumulative NPV. The mean value of the cumulative NPV for the UK tunnel market and global market in the year 2056 are US$ 58 million and US$573 billion respectively.

Acknowledgement

We greatly appreciate continuous supports given by Dr Kenichi Soga (University of Cambridge) and Dr Peter Bennett (University of Cambridge), who made huge contribution to this research project. We would also like to thank Chris Chew and Tim Simpson (Metronet) who provided us useful information about tunnel projects and allowed us to attend their internal meeting. Finally, we would like to acknowledge the CMI who gave us this opportunity to conduct such an interesting project.

1. Introduction

Millions of pounds are spent each year improving the asset value of aging infrastructure, such as tunnels and pipelines[1]. SMART Infrastructure is an innovative sensor system that provides real-time wireless information about the state of critical infrastructure. It is designed to monitor aging infrastructure, as well as to increase the capabilities of infrastructure for efficient maintenance. The potential application of SMART technology varies from bridges to dams, as shown in Figure 1.

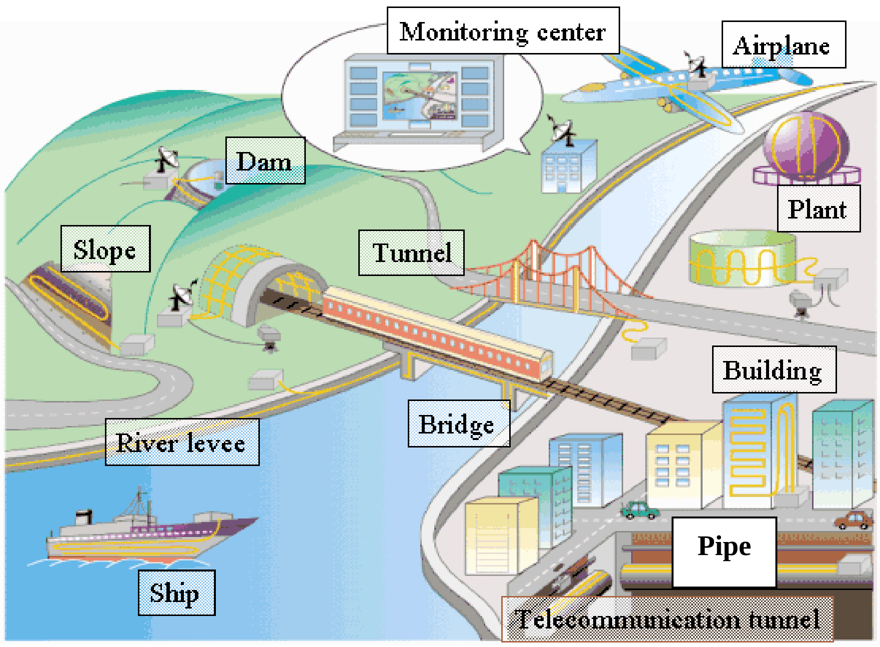

Figure 1 Applications of SMART sensor system
Source: Cambridge University Engineering department

[1] According to e.g., Thames Water (2005), Ofwat (www.ofwat.gov.uk) or Transport of London (www.tfl.gov.uk)

The failure of water pipelines or tunnels could result in catastrophic events. Reactive maintenance or measures can be very expensive and there is currently a lack of monitoring capabilities. This SMART technology could allow tunnel collapses and pipeline breaks to be averted. Therefore, social (reduction in disruption and loss of life) as well as direct economic benefits are expected. Miniaturization and improved battery life (or power harvesting) could reduce the costs down to below £50 per sensor from the current level of £500, according to SMART sensor developers. This could lower the cost of monitoring the infrastructure, which would attract operators to invest in large numbers of these SMART sensors.

The SMART sensors are able to share information across a range of agencies without human intervention. Thus, false readings can be corrected automatically and further incidents should be avoided. However, there will be an upfront cost of harmonizing the systems across the agencies. The SMART sensor developers argue that competitors will be highly likely to develop systems to monitor bridges and buildings, but there is less chance of this happening for tunnels and pipelines. There is even less chance that anyone else will develop the sharing capability across agencies.

This paper presents the model that assesses the impacts of this new technology, and the findings to date. The probabilistic cost benefit analysis, which takes into account of the future uncertainty, is conducted using the Monte Carlo simulation technique. The paper consists of four sections. The next section describes the framework of a model to calculate the social costs and benefits of continuing to develop SMART infrastructure, followed by the explanation of the data used in section 3. Section 4 presents the findings and the conclusion is given in Section 5.

2. Model

2.1. Model framework

The project assessment period is set to be 50 years (base year 2006), which is assumed to be long enough to assess the expected impacts from market penetration of SMART infrastructure. According to the experts from Metronet, approximately 30 years period could cover the impacts of the technology. The model consists of four regional segmentations - United Kingdom (UK), where SMART Infrastructure is developed, is selected as a focus region, with European Union (EU) (excluding UK), US and the rest of the world (ROW) being expressed using multipliers to the focus region.

There are two scenarios underlying the model, the baseline scenario and the SMART development scenario, as described below.

<u>Scenarios:</u>

Baseline – World without SMART development, but with natural improvement of the sensor system

SMART – World with SMART; the improvement of the sensor system can be expected to be much faster than the baseline case due to this innovative technology development

Figure 2 depicts the model framework, which examines the possible impacts of the SMART infrastructure development. There are three phases of the project – development, harmonization and market penetration. The model concept in Figure 2 illustrates the decision logic. First, we need to decide whether to fully develop the SMART sensor system. If we decide to develop and succeed in the commercialization, possible benefits are expected. If we do not succeed, we lose the development costs, which are already invested. If we further extend the market to outside the UK, further benefits are expected with no development costs, but some extra modification and harmonization costs are still necessary. Competitor consideration is included in the model framework, as competitors might appear in the market after a certain period. The possibility of failing to develop the SMART sensors successfully is also considered in the model, therefore, the expected impacts are multiplied by the probability of success or failure.

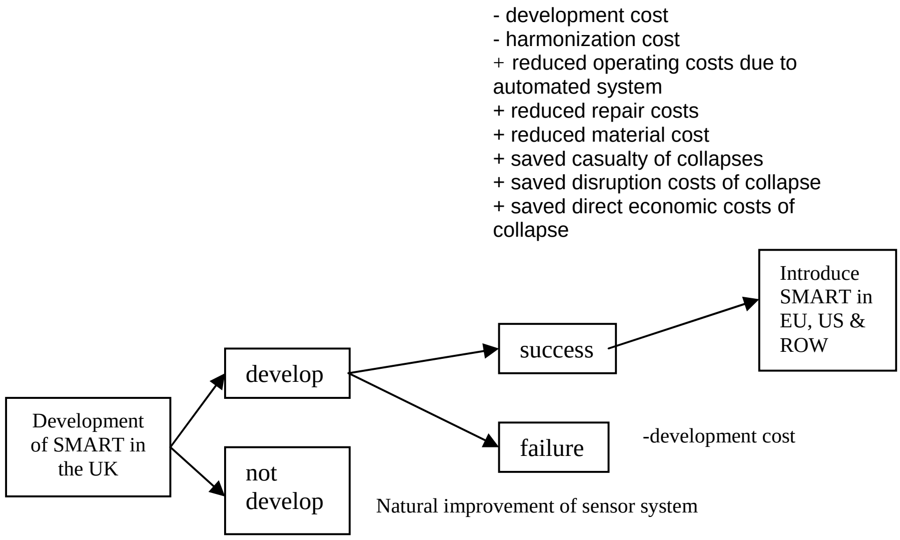

Figure 2 Model framework

2.2. Model parameters

Table 1 lists the eight categories of costs and benefits used in the model.

Table 1 Costs and benefits calculated by the model

Benefits	Costs
Saved O&M costs	Development cost
Saved repair cost	Harmonizing costs
Saved material costs	
Reduced collapse rate Saved casualty Saved disruption cost Saved economic damage cost	

The SMART sensor system detects failures of infrastructure at an early stage without any human inspection involved. The sensor also identifies the specific area which needs repairs, therefore unnecessary ground-digging is avoided. Thus, operation & maintenance as well as repair costs are expected to be significantly reduced from the current level. The material costs of SMART sensors are expected to be much lower than the current system, even though installation costs will be needed. In the model, the extra battery changing costs of SMART sensors are deducted from the overall saved O&M costs, and the extra installation costs are deducted from the overall saved material costs. The early identification feature of the SMART sensor system could lead to the reduced rate of tunnel or water pipeline collapses, which lowers the disruption damage (water/traffic, business/school forced to close), direct economic damage costs (infrastructure damage, flooding, ground water/soil contamination due to sewage) and possible casualties. The model does not include the replacement costs of SMART sensors explicitly, which are embedded in the installation costs. This is due to the fact that the exact life period of the SMART sensor system is currently not well known, according to the developers.

2.3. Key model equations

The following equations are used in the model to calculate the key variables.

(1) Total development cost *= development cost to date, if t=0,*
= (max development cost ($))*(((t+1)-1)/time of max development cost ($)), if t<time of max development cost + 1,
= (max development cost ($))(1-((t-time of max development cost-1)/(extra development time-time of max development cost)), if t<=extra development time+1,*
= 0, otherwise

(2) Harmonization cost *= (max harmonization cost ($))*(((t+1)-time of max harmonization cost-1)/(harmonization time), if t<extra development time+ time of max harmonization cost+1,*
= (max harmonization cost ($))(1-((t-extra development time-time of max harmonization cost-1)/(extra harmonization time-time of max harmonization cost)), if t<=extra development time+ harmonization time+1,*
= 0, otherwise

(3) Saved O&M cost *= ((unit O&M cost ($/km))*(saved % of O&M cost due to SMART)*((pipe market served by SMART (km)) – (battery changing cost ($/sensor)*(number of SMART sensors required))*

(4) Saved repair cost *= ((unit repair cost ($/km))*(saved % of repair cost due to SMART)*((pipe market needing repair (km))*

(5) Saved material cost *= ((unit material cost ($/km))*(saved % of material cost due to SMART) + ((installation cost ($/sensor))*(additional SMART sensors required)*

(6) Saved casualty *= (casualty valuation ($/person))*(number of casualties per collapse)*(reduced collapses due to SMART (collapses))*

(7) Saved disruption cost *= (disruption damage ($/collapse))*(reduced collapses due to SMART (collapses))*

(8) Saved economic damage cost of collapse *= (direct economic damage of collapse ($/collapse))*(reduced collapse due to SMART (collapses))*

(9) Total cost (TC) = development costs + P*harmonization cost $/year

(10) Total benefit (TB) = P*{saved O&M cost + saved repair cost + saved material cost + saved casualty + saved disruption damage + saved economic damage + saved sub-ground valuation} ***$/year***

$$\textbf{(11) Net present value} = \sum_{t=0}^{T} (1+dt)^{-t}(TBt-TCt) \qquad \$/year$$

where TB=total benefits, TC=total costs, dt=discount rate, and NPV_T= net present value at time T, P=probability of technical & commercial success of SMART

2.4 Main features of the model

2.4.1. Market penetration

The SMART infrastructure is first introduced in the UK, and then in the EU and US, follower by the rest of the world. The market penetration rate of the SMART infrastructure increases gradually, and reaches the maximum target rate. After a certain period, competitors might start appearing and the market penetration growth rate starts decreasing. The model uses a one form of a logistic function to portrait the market penetration behavior of SMART infrastructure. The logistic function exhibits an approximately exponential growth at the initial stage, followed by a slows-down of the growth due to competition, and the growth stops finally at maturity[2]. The equation to calculate the market penetration rate in the model is presented below.

(12) Market penetration rate =0, if t<extra development time+ harmonization time,
=max target market penetration rate/(1+(100))*(extra development time+ harmonization time+ penetration time))^2)*(EXP(t/1.5)), if t<=extra development time+ harmonization time+ time competition appears,
=(max target market penetration rate- market penetration rate decrease due to competitors)/(1+((100)*(extra development time+ harmonization time+ penetration time))^2)*(EXP(t/1.5))), otherwise ***%***

[2] See http://en.wikipedia.org/wiki/Logistic_function for more details

2.4.2. Multipliers

The model is developed at several stages. First, the UK water pipe assessment model is developed as a core model for the following reasons: i) SMART is developed in the UK, ii) water pipe related data is relatively easy to obtain compared to tunnel related data iii) the UK focused model is useful for the SMART sensor developers in their further funding application in the UK. Then, the global water pipe model is developed applying multipliers using the UK as a focus region. The global tunnel model is developed in a similar manner using multipliers with the global water model as a base. Finally, the global model with all the applications is developed by combining the results of the global water pipe and tunnel applications plus other industry applications, in which multipliers are used with the global tunnel model being a base model, since similar behaviors are expected.

3. Data

3.1. Input parameters

Data are collected from various sources including a series of meetings with the SMART Infrastructure project members as well as experts in the field, literatures, annual reports and internet. Data for all the input parameters are listed in Appendix. A range of values (minimum, most likely and maximum) is used instead of using just a single figure for each input. A large rage is used for those data with large uncertainty. All the input data are assumed to follow a triangular distribution. Hence, a range of outcome is obtained, which gives more robust results when dealing with huge future uncertainty.

3.2. Discount rate

When conducting cost benefit analysis, what discount rates should be used is a difficult decision. There is no single rate that satisfies all the requirements for all projects. The appropriate discount rate is project-specific (Lind 1982). This analysis applies the commonly used values for infrastructure projects. The UK government for water project usually uses the discount rate of 3.5% (www.dwi.gov.uk), while 3% is commonly used for tunnel projects (Vronwenvelder & Krom 2004).

4. Findings

The Monte Carlo simulation with 10,000 iterations is run using Palisade @RISK software. This section presents the findings of the model runs, the UK water pipe application, and the UK tunnel application, followed by the global applications.

4.1. UK water pipe application

The findings of the UK water pipe model present the expected impacts of the SMART infrastructure when the technology is commercialized in the UK water pipe market.

4.1.1. Market penetration

The market penetration rate gradually increases after the year 2023, until the maximum target market penetration of around 27% is reached in the year 2037, as shown in Figure 3. The market penetration growth rate decreases after competitors might start appearing.

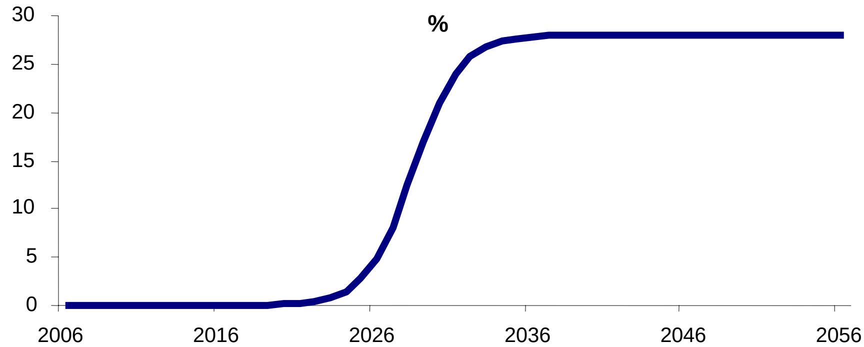

Figure 3 Market penetration
Source: CBA model runs

4.1.2. Number of SMART sensors required

The number of SMART sensors required start increasing after the development completion and peaked at approximately 20 million sensors in the year 2029, followed by a gradual decrease once maximum target market penetration is reached as shown in Figure 4.

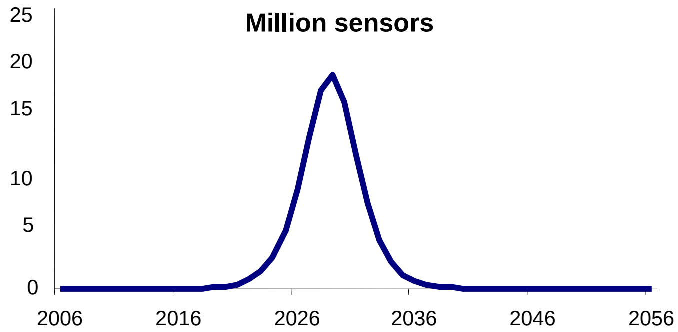

Figure 4 Additional SMART sensors required by year
Source: CBA model runs

4.1.3. Development & harmonization costs of SMART sensors

SMART infrastructure is developed in the UK, which initially requires large development costs of approximately US$3.4 million at the peak, as shown in Figure 5a. If development delays occur, extra cost will be necessary. After development is complete, further periods are required for harmonization (built required facilities, transition costs of switching the system from the current to the new one including training) as shown in Figure 5b. The necessary harmonization cost for the SMART sensor system seems to be much smaller than the development costs, as no significant extra infrastructure is necessary for SMART infrastructure. Note that the development and harmonization costs for the tunnel application are much smaller fraction of the costs for the water application, as only some modifications are needed for different applications once developed.

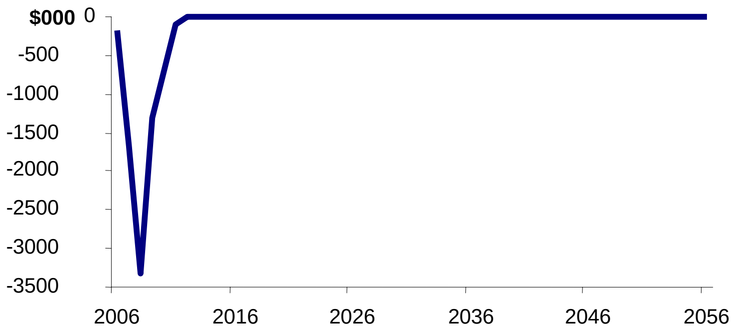

Figure 5a Development cost

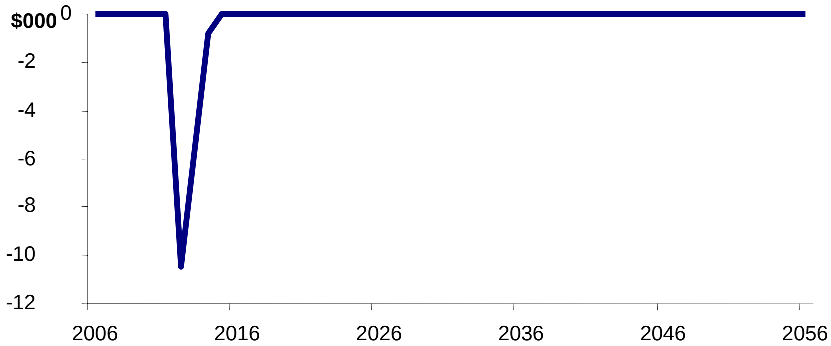

Figure 5b Harmonizing cost

Source: CBA model runs

4.1.4. Main impacts of SMART sensors

The SMART infrastructure can speed up the process of improving the current sensor system, generating direct economic benefits, such as reduced operating & maintenance costs due to its automated system, reduced repair costs, reduced material costs as well as indirect benefits of reduced collapse rates. Figure 6 shows that the huge benefit of saved disruption damage costs due to reduced water pipe burst rate by the application of SMART sensors can be expected. The other significant benefit is the saved operation and maintenance cost, according to the model. The present values of saved disruption damage as well as O&M costs (cumulative) in the year 2056 are US$15 billion and $6 billion restively.

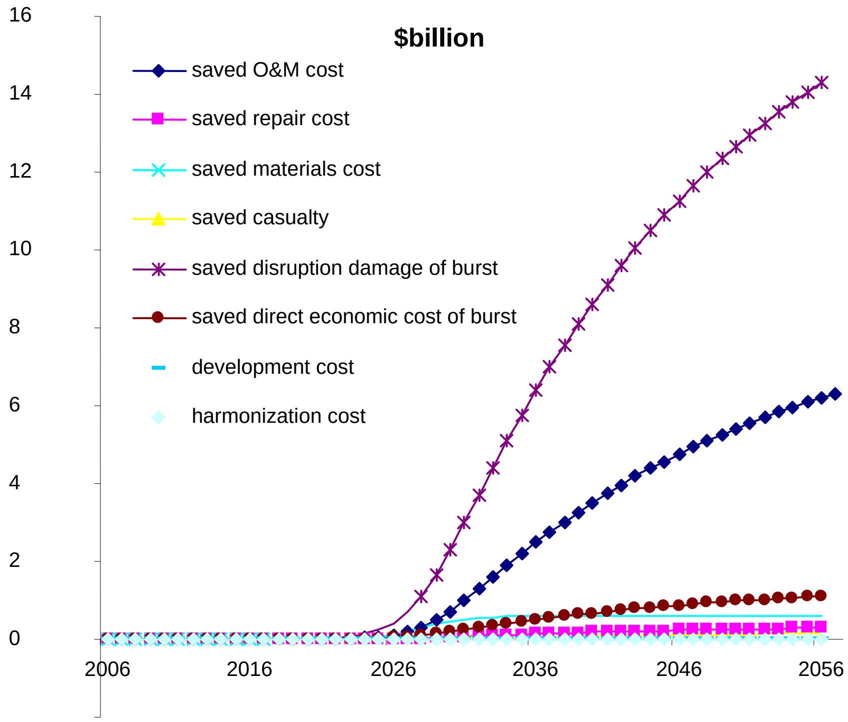

Figure 6 **Present values of the variables (cumulative)**
Source: CBA model runs

4.1.5. Net Present Values

Summing all the expected costs and benefits produces an annual NPV as shown in Figure 7a. The NPV starts increasing in the year 2021 and shows the steady growth until the year 2031. Between the year 2026 and 2031, significant growth rates of an annual NPV can be expected. After reaching the peak in the year 2031, the annual NPV starts decreasing gradually. The cumulative NPV is depicted in Figure 7b. The 5th percentile, mean and the 95th percentile of the cumulative NPV in the year 2056 are US$6, 23.7, 56.2 billion respectively.

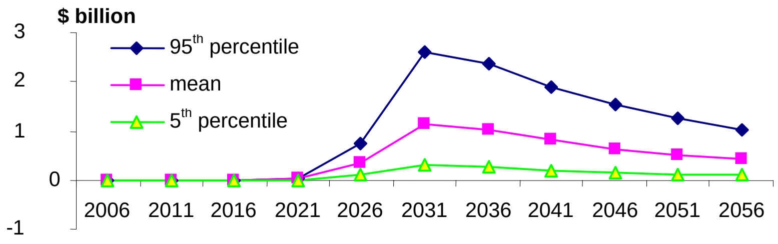

Figure 7a Annual NPV for the UK water pipe application

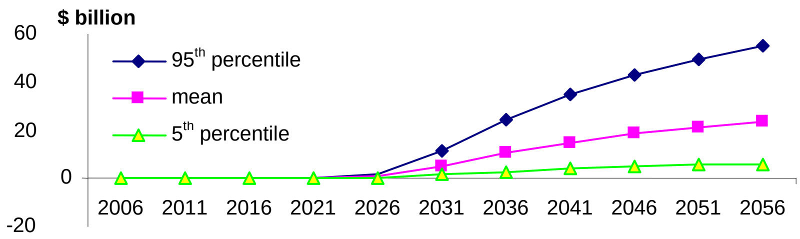

Figure 7b Cumulative NPV for the UK water pipe application
Source: CBA model runs

4.1.6 Sensitivity analysis

The sensitivity analysis identifies which parameters have significant impacts on the cumulative net present value. The result shows that the base year disruption damage cost has the most significant impact with the factor of 0.63, follower by the maximum target market penetration rate with the factor of 0.53 as shown in Table 2. The discount rate also has the significant negative impact on the cumulative NPV with the factor of 0.36. This means that if higher discount rates are used, the lower NPV will be obtained. Therefore, we have to be careful when we select the discount rate as the outcome is sensitive to our decision.

The other notable parameters are the annual number of pipe bursts and reduced collapse rate due to SMART technology as listed in Table 2.

Table 2 Sensitivity analysis for the UK water pipe model

Parameter	**Unit**	**Student b coefficient***
Base year disruption damage cost	$/year	0.63
Max target market penetration rate	%	0.53
Discount rate	%/year	-0.36
Annual number of pipe burst	bursts/km	0.14
Reduced collapse rate due to SMART	%	0.09

*: The student b coefficient is a coefficient calculated for each input parameter in the regression equation. The input parameter values are regressed against the output (NPV). Source: Sensitivity analysis runs

4.2. UK tunnel application

The UK tunnel model assesses the impacts of the SMART technology application to the tunnel industry in the UK. The data used in the UK tunnel model are multipliers to the UK water pipe model (Appendix A.2).

4.2.1. Cumulative NPV

The findings of the UK tunnel application model show much smaller positive impacts of SMART infrastructure, compared to the UK water pipe application. For the 5^{th} percentile of the cumulative NPV, the costs start recovering in the year 2051 onwards as shown in Figure 8. The reasons behind this could be the extra costs of SMART infrastructure, namely extra installation costs and material costs becoming high, as numerous sensors are required for this new system. These costs outweigh the expected benefits, since much smaller market being served (much shorter total length of tunnels than water pipes), so lower impacts are expected. The tunnel collapse rate is also likely to be much lower than the water pipe burst rate, therefore, lower benefits of the reduced collapse rates are expected. The 5th percentile, mean and the 95th percentile of the cumulative NPV for the UK tunnel market in the year 2056 are all positive - $2, 58 and 166 million respectively as shown in Figure 8.

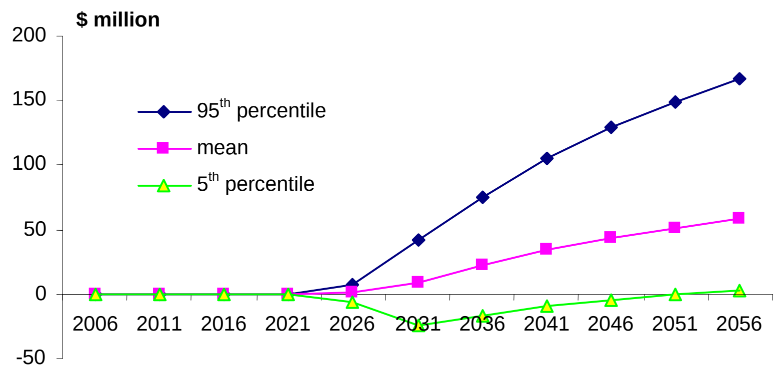

Figure 8 Cumulative NPV for the UK tunnel model
Source: CMA mode runs

4.2.2. Sensitivity analysis

The sensitivity analysis for the UK tunnel model shows very similar results to the UK water pipe model as shown in Table 3. The most significant parameters are the base year disruption damage costs and the maximum target market penetration rate with the factor of 0.35. The parameters specific to the UK tunnel model are the % saving in material costs, tunnel length multiplier, and tunnel collapse rate multiplier.

Table 3 sensitivity analysis for the UK tunnel model

Parameter (all water pipe application)	**Unit**	**Student b coefficient***
Base year disruption damage cost	$/year	0.35
Max target market penetration rate	%	0.35

% saving in material costs	%	0.28
Multiplier of tunnel length		0.27
Multiplier of disruption cost		0.26
Multiplier of tunnel collapse rate		0.25
Discount rate	%/year	-0.24

Source: Sensitivity analysis runs

4.3. Global applications

The global model assesses the impacts of the SMART infrastructure application to all the possible industries in the whole world. Due to limited data sources, the global model data heavily relies on the UK water pipe model like the UK tunnel model (Appendix A.3), and it is still at a trial stage.

4.3.1. Cumulative NPV

In Figure 9, the 5th percentile of the cumulative NPV shows that benefits might not outweigh the benefits until the year 2051, as in the UK tunnel model. This is possibly due to the extra costs required by the SMART infrastructure - battery changing costs of SMART sensors and extra material costs of SMART sensors as a result of much larger number of sensors being required for this new technology. The other possible reason is that the infrastructure in some regions might not be as old as the UK, therefore the benefits of the SMART sensors could be smaller. The 5th percentile, mean and the 95th percentile of the cumulative NPV in the year 2056 are US$ 35, 573, 1617 billion respectively as shown in Figure 9.

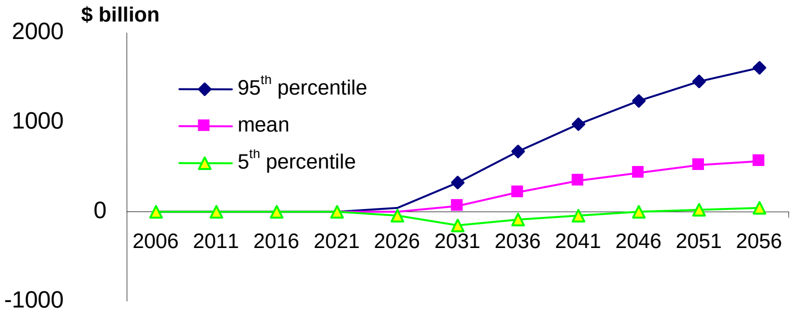

Figure 9 Cumulative NPV for the global model
Source: CBA model runs

4.3.2. Sensitivity analysis

The sensitivity analysis for the global model shows fairly similar results to the UK water pipe and tunnel models, as listed in Table 4. All the significant parameters are the same as before with a similar magnitude, except one new parameter showing a significant impact on the NPV, namely the EU multiplier of material cost saving due to the SMART technology.

Table 4 Sensitivity analysis for the global model

Parameter (all water pipe application)	**Unit**	**Student b coefficient***
Base year disruption damage cost	$/year	0.62
Max target market penetration rate	%	0.40
Discount rate	%/year	-0.28
EU multiplier of material cost saving		0.15
Annual number of pipe burst	Bursts/km	0.14

Source: Sensitivity analysis runs

5. Conclusion

This paper has assessed this innovative new automated SMART sensor development project, which is likely to make a huge contribution to the industries that are operating with aging infrastructure systems, as a large sum of money for monitoring, operation, maintenance and repairing are currently required.

Those industries operating large infrastructures such as water pipelines and tunnels are generally reactive to problems. Water authorities that assess their asset management scheme historically emphasize on repairing pipeline failures rather than preventing the failure (Eiswirth et al 2001). However, they need to be proactive, making appropriate planning and operational strategies before problems occur in order to operate cost efficiently. The SMART infrastructure is a system which enables industries to be more strategic when dealing with aging infrastructure, and the model in this research confirms its effectiveness. The mean values of the cumulative NPV for the UK water pipe, UK tunnel and global applications are US$ 23.7 billion, 58 million, and 573 billion respectively.

The SMART infrastructure seems to be economically sound, partly due to its relatively low development and harmonization costs. Based on our findings, the project is highly likely to generate significant benefits both in terms of economic and social, therefore strong investment opportunities are indicated. This positive outcome heavily relines on the two characteristics of the SMART sensors. First, the SMART technology would significantly reduce operation & maintenance costs of those industries with aging infrastructures, as the SMART sensors are completely automated. The disruption damage costs are also likely to be reduced significantly since the technology allows the industries to deal with problems beforehand not reacting after the catastrophic events had already occurred.

Moreover, the SMART infrastructure has a wireless feature, with which the sensors are relatively inexpensive to install, as usual wiring systems require expensive wiring between the sensors and the data acquisition system (Lynch et al. 2006). However, operators need to bear in mind that installing numerous sensors might not be completely negligible costs, as shown in the findings. The model results also show that battery changing costs of numerous SMART sensors can be expensive. Thus, power harvesting using available energy in the underground could be an alternative cost effective option.

In this research, maximum efforts are made to find as accurate data as possible for the analysis. However, data related to infrastructure projects are generally difficult to obtain since they are often not publicly available due to data sensitivity. Some sensitive data can be updated by interviews with experts. Further investigations to obtain better data would be conducted in the future research in order to improve the results. The input data are easily replaceable and the model is easily re-run with the new data set.

Appendix

A. Data

Table A.1. UK water pipe application

Parameter	**Values (min, most likely & max)**	**Description of each value**
Extra development time	(3, 3.5, 6) years	CED estimates
Harmonization time	(2.9, 3, 3.1) years	Ibid.
Penetration time	(9, 10, 11) years	Ibid.
Year competition appears	(2, 3, 4) years	Ibid.
Base year water pipes	(35,40, 45)0000km	www.ofwat.gov.uk
Time trend of water pipes	(0, 0.05, 0.1)%/year	Ibid.
Base year sensors	(50, 100, 150)/km	CED estimates
Time trend of sensors	(0, 0.1, 0.2)%/year	Best assumption
Extra SMART sensor multiplier	(9.8, 10, 10.2)	CED estimates
Max target market penetration	(10, 30, 80)%/year	Ibid.
Competitor multiplier for market penetration decrease	(0.2, 0.3, 0.4)	Ibid.
Total development cost	(180,189,190)000$	Ibid.
Extra development cost	(546,560,600)0000$	Ibid.
Base year installation cost	(3, 5, 10)$/sensor	Ibid.
Time trend of installation cost	(-0.1, 0, 0.1)%/year	Best assumption
Harmonization cost	(1, 2, 5)0000$	Best assumption
Parameter for development cost peak	(0.1, 0.2, 0.5)	Morimoto & Hope (2004)
Parameter for harmonizing cost peak	(0.1, 0.2, 0.5)	Ibid.
% of pipe require repairs	(20, 40, 50)%	CED estimates
Time trend of % pipe	(0, 0.05, 0.1)%/year	Best assumption
Pipe bursts	(0.2, 0.3, 0.4)/km/year	www.ofwat.gov.uk
Casualty valuation	(3, 4.5, 5) 000000$/person	Morimoto & Hope (2004),Vronwenvelder & Krom (2004)
Time trend of casualty	(0.1, 1, 3)%/year	http://www.tswoam.co.uk
Casualty number	(1,2,3) 10^{-3}/burst	Best assumption
Time trend of casualty	(-0.1, 0, 0.1)%/year	Ibid.

number		
Disruption damage cost	(5, 10, 4000)00$/burst	www.house.gov
Time trend of disruption cost	(-0.1, 0, 0.1)%/year	Best assumption
Economic damage cost	(1, 5, 25)000$/burst	Virgin Radio news 4 July 2006
Time trend of damage cost	(-0.1, 0, 0.1)%/year	Best assumption
Probability of success	(80, 95, 100)%	CED estimates
Discount rate	(2, 3.5, 6)%/year	www.dwi.gov.uk
O&M cost	(28,28.8,29)000$/km/year	www.ofwat.gov.uk
Time trend of O&M cost	(-2.6, -2, 0)%/year	Ibid.
Repair cost	(44, 44.5, 45)00$/km	www.ofwat.gov.uk
Time trend of repair cost	(-2.6, -2, 0)%/year	Best assumption
Material cost	(900, 920, 950)$/sensor	CED estimates
Time trend of material cost	(-0.1, 0, 0.1)%/year	Best assumption
Time trend of collapse rate	(-1.5, -1.2, -0.8)%/year	www.ofwat.gov.uk
Time trend of time trend of collapse rate	(-0.1, 0, 0.1)%/year	Best assumption
% saving in O&M	(10, 30, 40)%/year	CED estimates
Time trend of O&M saving	(-0.1, 0, 0.1)%/year	Best assumption
Battery change cost	(1, 4, 5)$/sensor	CED estimates
Time trend of battery change cost	(-0.1, 0, 0.1)%/year	Best assumption
% saving in repair cost	(10, 40, 60)%/year	CED estimates
Time trend of repair saving	(-0.1, 0, 0.1)%/year	Best assumption
% saving in material cost	(90, 91, 95)%/year	CED estimates
Time trend of material saving	(-0.1, 0, 0.1)%/year	Best assumption
Reduced collapse rate	(50, 70, 80)%/year	CED estimates
Time trend of reduced collapse	(-0.1, 0, 0.1)%/year	Best assumption

Note: CED (Cambridge engineering department)

Table A.2. Tunnel application multipliers

Parameter	**Values (min, most likely & max)**	**Description of each value**
Tunnels	(0.001, 0.003, 0.005)	www.tfl.gov.uk

Extra development cost	(0.0001, 0.0005, 0.001)	CED estimates
Harmonization cost	(0.2, 0.5, 0.7)	Best assumption
Tunnel collapse	(0.01, 0.05, 0.1)	Ibid.
Collapse casualties	(200, 500, 800)	Ibid.
Disruption damage cost	(1, 5, 500)	The Times, 2 July 2005
Direct economic cost	(1, 2, 5)	Best assumption
Discount rate	(0.9, 0.98, 1)	Vronwenvelder & Krom (2004)
O&M cost	(0.5, 0.8, 1)	Best assumption
Repair cost	(0.7, 1, 1.3)	Ibid.
Multiplier of SMART applications to other industries	(0, 0.1, 0.25)	CED estimates

Note: If input values are the same as the water pipe application, figures are not listed here

Table A.3. Global application multipliers

Parameter	**Values (min, most likely & max)**	**Description of each value**
Tunnel	(0.001, 0.003, 0.005)	www.tfl.gov.uk
Extra development cost	(0.0001, 0.0005, 0.001)	CED
Harmonization cost	(0.2, 0.5, 0.7)	Best assumption
Tunnel collapses	(0.01, 0.05, 0.1)	Ibid.
Casualty of collapses	(200, 500, 800)	Ibid,
Collapse disruption costs	(1, 5, 30)	Times 2 July 2005
Direct economic cost	(1,2,5)	Best assumption
O&M cost	(0.5, 0.8, 1)	ibid.
Discount rate	(0.9, 0.98, 1)	Vronwenvelder & Krom (2004)

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