


Infrastructure and material criticality: project findings report

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Investigating Material Criticality

Highways Agency

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Document history

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Investigating Material Criticality

Highways Agency

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Executive summary

Halcrow, working in partnership with the University of Leeds and TRL, were commissioned by the Highways Agency to develop a framework which could be used to assess the criticality of materials used by the Highways Agency in delivering their core functions. Material criticality is primarily concerned with the disruption of supply of vital materials i.e. materials whose scarcity would impinge significantly on an organisation. This could be by way of cost escalation or restricting typical organisational activities for example. In the worst cast, the impact would be catastrophic to the organisation.

This project has developed a framework for considering material criticality. Material criticality, in the context of infrastructure, is a measure of the potential threat posed to the continued service provided by a system of infrastructure assets by supply disruption of vital materials. The framework for assessing criticality (developed by the University of Leeds team and adapted by this project) considers a material's Potential for Supply Disruption (PSD) and a function's Exposure to Supply Disruption (ESD).

The framework will enable the Highways Agency to investigate the extent to which its core functions are exposed to risks posed by supply disruption of key materials. Through consultation, the project has sought to understand the extent to which Highways Agency staff and delivery partners currently consider criticality issues.

Clearly defining core functions is a key step in assessing criticality – this establishes the 'goals' the Highways Agency is measuring criticality against. Core functions relate to the services the Highways Agency provides to its 'customers' rather than the activities it undertakes (e.g. safe roads and reliable journey times, rather than operating and maintaining the network).

Potential for Supply Disruption (PSD) is a material property indicative of the potential that a material may experience supply disruption based on factors such as concentration of supply, environmental constraints on extraction, and technical factors such as co-mining and projected production vs. requirement trends.

Exposure to Supply Disruption (ESD) is a property of the asset or function indicative of the severity of the effect of a supply disruption on the delivery of the function. It is primarily based on goal sensitivity (how important is the asset to the overall goal or function) and price sensitivity (what proportion of the price of a technology is associated with the critical material in question).

The two metrics, PSD and ESD, may be reported individually or combined (multiplied) into a single criticality measure (analogous to multiplying a probability and severity measure into a risk index). A simple indicative plot of PSD and ESD is shown in Figure 2 in the form of a risk matrix. The criticality scores for all materials providing a core function can be graphed to give an overall indication of criticality for a function.

When considering options for addressing criticality issues, either the PSD can be addressed, though substituting the material or changing the material specification or the ESD can be addressed, though making changes to how the core function is delivered by the assets as exemplified by the red arrows.

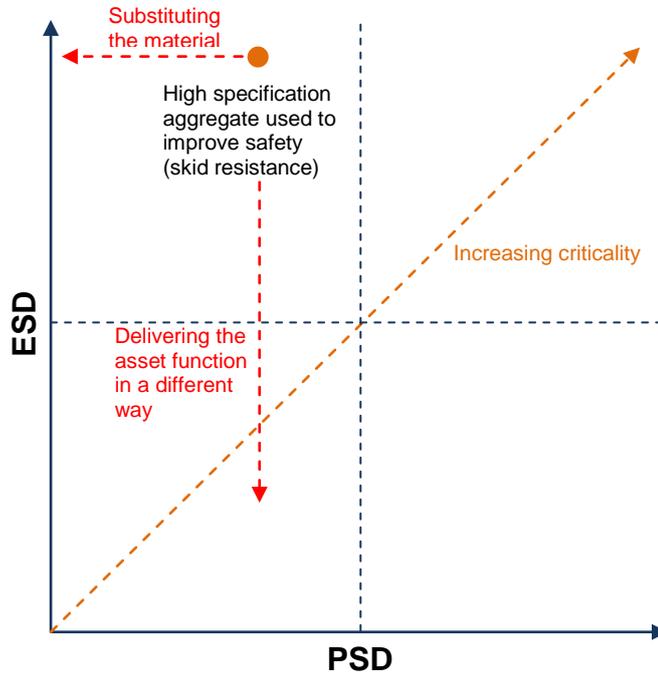


Figure 2: Criticality matrix

In order to assess the combined effect of PSD and ESD, the Highways Agency’s core functions have been mapped to the key materials which provide these functions (via their network of assets). Linking materials to the core functions of the Highways Agency via the mapping exercise undertaken by this project is a new approach and allows modelling of criticality issues and application of the criticality framework.

Figure 5 shows an example of this network for functions assets and materials, in this case for high specification aggregates.

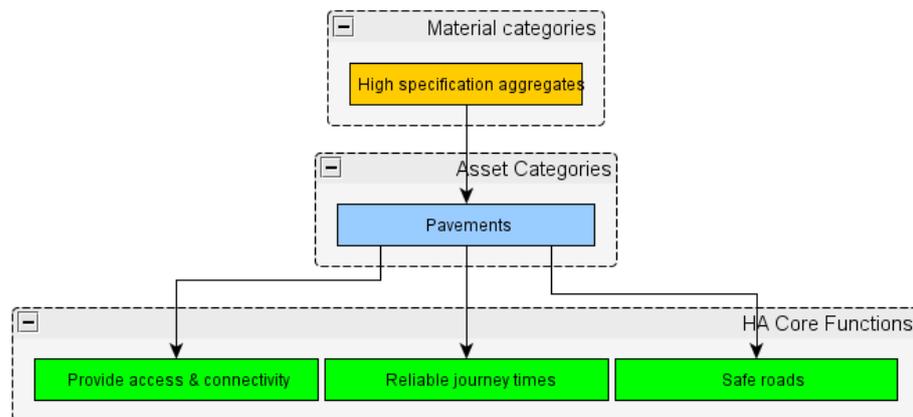


Figure 5: material – high specification aggregates – asset and core function network (figure produced using yEd Graph Editor software)

Through attempting to apply the draft criticality framework this project has shown the potential methods to quantify and consider criticality and demonstrated how it is possible to apply the framework. The outline assessment of criticality for the Highways Agency and the materials used in their network has shown there are significant data gaps and levels of uncertainty in quantifying both PSD and ESD metrics.

This project undertook a consultation exercise to gain an understanding of if and how material criticality issues are currently considered by the Highways Agency. This found that material criticality issues are not routinely/systematically considered by the Highways Agency or their delivery partners. There have been some isolated examples of supply disruption events, e.g. winter salt and steel. Where examples of criticality issues are cited, Highways Agency/ supplier response tends to have been reactive rather than proactive.

In general, criticality risk is seen as low – with some concern cited over technology assets, bitumen and the impact that energy price may have. Currently there is a lot of uncertainty over the potential for future supply disruption and the impact it may have.

There is a recognised shift towards the greater deployment of electronic technology on the network. However, there is also uncertainty over whether this trend will continue as technology is anticipated to increasingly move ‘in-car’. There is also uncertainty over materials used to provide technology assets and whether future criticality issues may arise. It is difficult to decide what decisions should be taken when there is a landscape of uncertainty due to future change that could influence the materials usage significantly.

Further research is required in order to refine the framework developed by this project and apply it to the full range of Highways Agency’s functions and assets to provide a full picture of material criticality. This will allow the Agency to develop a greater understanding of the potential risks posed by material criticality issues.

Summary of key findings:

- There is significant value in investigating the relative criticality of materials to the functions delivered by the Highways Agency as it will allow the Agency to identify where resource should be targeted for further research and data gathering to reduce exposure to material criticality issues.
- Material criticality issues are not routinely/ systematically considered by the Highways Agency or their delivery partners.
- There are significant data gaps and levels of uncertainty in quantifying both PSD and ESD metrics.
- There is uncertainty over materials used to provide technology assets and whether future criticality issues may arise.
- The relative magnitude of the different factors making up a combined criticality score has significant implications when considering management or mitigation options (for example the relative importance of the potential for supply disruption and the exposure to supply disruption metrics).

1 Introduction

Halcrow, working in partnership with the University of Leeds and TRL, were commissioned by the Highways Agency to develop a framework which could be used to assess the criticality of materials used by the Highways Agency in delivering its core functions. Material criticality is primarily concerned with the disruption of supply of vital materials i.e. materials whose scarcity would impinge significantly on an organisation. For example, by cost escalation or restricting typical organisational activities. In the worst cast, the impact could be catastrophic to the organisation.

This report presents the project findings and conclusions, and is supported by a Literature Review, which is appended to this report, see Appendix C.

1.1 Aims and objectives

The project aims to provide a framework for the Highways Agency to assess material criticality. The framework will enable the Highways Agency to investigate the extent to which its core functions are exposed to risks posed by supply disruption of key materials. Through consultation, the project has sought to understand the extent to which Highways Agency staff and delivery partners currently consider criticality issues.

The stated objectives for the project are:

- To understand the criticality risks associated with materials used in the maintenance, improvement and operation of the strategic road network.
- To provide a basis for ensuring future security of supply of vital materials needed to operate the strategic road network to the expected standards.
- To understand where potential resource vulnerabilities may exist.
- To explore opportunities from increased diversity of supply and substitutability.

1.2 Definitions

The key terms for this project are defined in detail in the Literature Review. A summary is provided below:

Material criticality, in the context of infrastructure, is a measure of the potential threat posed to the continued service provided by a system of infrastructure assets by supply disruption of vital materials. The framework for assessing criticality (developed by the University of Leeds team and adapted by this project) considers a material's Potential for Supply Disruption (PSD) and a function's Exposure to Supply Disruption (ESD).

A **core function** is a service provided by an infrastructure asset, for example, in the context of a road this could be connectivity or safety.

Potential for Supply Disruption (PSD) is a material property indicative of the potential that a material may experience supply disruption based on factors such as concentration of supply, environmental constraints on extraction, and technical factors such as co-mining and projected production vs. requirement trends.

Exposure to Supply Disruption (ESD) is a property of the asset or function indicative of the severity of the effect of a supply disruption on the delivery of the function. It is primarily based on goal sensitivity (how important is the asset to the overall goal or function) and price sensitivity (what proportion of the price of a technology is associated with the critical material in question).

Vital materials are those materials necessary to provide the core functions of the Highways Agency. Vital materials are used in the range of Highways Agency assets which provide their core functions.

Criticality **risk** is a measure of the vulnerability of the Highways Agency's delivery of their core functions to the supply risk of vital materials. PSD and ESD may be reported individually or combined (multiplied) as a risk metric into a single criticality measure (analogous to multiplying a probability and severity measure into a risk index).

1.3 Project Approach

The project has followed five key stages:

Literature review – the first stage of the project was to summarise existing relevant research and literature, the review focused on:

- infrastructure services and material consumption;
- existing material criticality and resource security studies;
- academic approaches to material criticality assessment;
- resource security and resource efficiency policies;
- existing approaches to risk-based asset management and managing supply risk; and
- future highways infrastructure.

Development of draft criticality framework – based on work undertaken by the University of Leeds, the project developed a criticality framework suitable for the Highways Agency.

Mapping Highways Agency core functions to materials – as a basis for the criticality assessment it was necessary to define the Highways Agency's core functions (services) and map material use to the provision of these functions.

Consultation – various consultation methods were used to engage with key stakeholders:

Stakeholder workshop - to gain insight to the relevance of material criticality to the various key Highways Agency functions; to agree the approach for assessing material criticality in the Highways Agency; to validate the critical path mapping of delivery of Highways Agency core functions to key materials, and to agree the approach to wider consultation and stakeholder engagement with the Highways Agency's key functions, their delivery partners and suppliers on material criticality.

Online questionnaire – to gather information from the Highways Agency on how material supply risk is perceived and managed and inform the direction of the project and its recommendations.

Telephone interviews/ data gathering – to gain an understanding of the nature of the supply chain of interest and to gather evidence to inform the ESD metrics of the criticality assessment.

Analysis/applying the framework – following the consultation and data gathering, we have attempted to apply the framework to the materials typically used in the Highways Agency network to appraise exposure to supply disruption for a selection of asset-function links.

1.4 Report structure

This report is structured into two main sections. Chapters 2 to 4 focus on the development and application of the criticality framework for the Highways Agency. Chapter 5 focuses on how criticality is currently considered by the Highways Agency (as explored by the consultation exercises). The findings and conclusions are summarised in Chapter 6.

2 Developing a framework for the Highways Agency to assess material criticality

2.1 The approach and framework

The assessment framework of material criticality developed by this project for the Highways Agency is based on on-going work being undertaken as part of the Undermining Infrastructure (UI) project at the University of Leeds.

The UI team is developing a framework to assess the criticality of materials essential for the transition to a low-carbon economy, as part of an EPSRC funded research project. This is the first attempt at developing a framework specifically designed for infrastructure, as opposed to regional or national economies or individual companies. Whilst the UI framework focuses on the criticality of materials to the low-carbon transition, this project investigates materials critical to the continued and future provision of functions/services that the Highways Agency provides, such as mobility and safety. This project aims to enhance the Highways Agency's understanding of the risk posed to the core functions from potential supply disruption of materials.

The framework uses a range of metrics to address the material's Potential for Supply Disruption (PSD) and the core service's Exposure to Supply Disruption (ESD). Scores are combined to arrive at figures for PSD and ESD which can be plotted against each other to determine the relative criticality of a material in a particular asset providing a given function or combined (multiplied) into a single criticality measure.

Criticality is currently a relative concept; it is not possible at this stage of development of the analysis methodology to arrive at an absolute probability of supply disruption. However, there is significant value in investigating the relative criticality of materials to the functions delivered by the Highways Agency as it will allow the Agency to identify where resource should be targeted for further research and data gathering to reduce exposure to critical materials.

Given the scope of this project, the assessment framework will be static in nature, i.e. it will not formally forecast each criticality metric into the future. However, where possible, it could inform estimates about future trends in criticality metrics. In order to forecast criticality risks it would be necessary to be able to consider how to quantify each individual criticality metric in future years. This may be possible in cases where forecast predictions are available for the potential future make up of highway's infrastructure in order to consider the future material demands of the network. The draft framework presented in Figure 1 displays the factors contributing to PSD and ESD along with their corresponding metrics.

The factors contributing to the criticality of a material are slightly different depending on the scale of the market for each material. For materials imported to the UK (e.g. copper), global supply chain characteristics contribute to the potential for supply disruption in the UK. For indigenously-

sourced materials (e.g. crushed rock aggregate), it is domestic factors that contribute. The Highways Agency’s high level of exposure to indigenous materials makes this a case study of particular practical, academic and political interest. The framework presented in Figure 1 shows draft metrics for both imported and indigenous materials.

A 0-1 scale is used for each metric, where a higher score indicates a higher contribution to criticality. Scoring is discussed in greater detail in the following sections.

	Contributory factors	Definition of metrics	Data requirements	Scoring nature and scale
Potential for supply disruption (PSD)	Concentration of supply	Measure of global concentration of supply: Herfindahl–Hirschman Index (HHI) or HHI for number of supplying quarries or producing companies	Suppliers and quantities of materials each supplies (nations for imported, companies or quarries for indigenous materials)	Calculated, 0-1 scale
	Environmental constraints on extraction	Environmental Country Risk (ECR) score or land-use data on planning constraints	Producing countries and quantities	Calculated, 0-1 scale
	Companion fraction	Mass fraction and price fraction of host ore or estimate of co-production	Mass and price fraction of materials (this may be difficult to do for aggregates)	Calculated, 0-1 scale
Exposure to supply disruption (ESD)	Sensitivity of asset to material	Contribution of material to technology/ infrastructure cost	Evidenced assumptions of dependence from expert interviewees	Judgement, 0/0.5/1
	Sensitivity of function to asset	Measure of the dependence of the core function being delivered on the technology/ infrastructure	Evidenced assumptions of dependence from expert interviewees	Judgement, 0/0.5/1

Figure 1: Criticality framework for the Highways Agency

2.2 Potential for Supply Disruption metric (PSD)

The PSD metrics describe properties of the material itself or its supply chain. PSD metrics are therefore calculated based on secondary information from a range of sources (including the US Geological Survey and Yale’s Environmental Policy Index). There are three metrics used to make up PSD:

- Concentration of supply – the Herfindahl–Hirschman Index (HHI): this is a measure of the number of sources available for a material; either globally for materials purchased on the international market or nationally for indigenously sourced materials (e.g. aggregates). The greater the number of sources available the lower the score and hence potential for supply disruption.
- Environmental constraints on extraction – Environmental Country Risk (ECR): this measure reflects the legislative requirements of the country from which a material is sourced which may place constraints on its supply and hence the availability of the material. The ECR score is used as a measure of these constraints, based on, for example, planning constraints. A higher score indicates a greater potential for supply disruption.
- Companion Fraction: this is a measure of the proportion of the production costs and material mass that are directly related to the material in consideration compared to the proportion related to the co-production of an associated material. For example, a material produced as a by-product, e.g. bitumen, will have a low mass fraction whilst a material produced without any co-production, e.g. timber will have a high mass fraction. These companion fractions are inverted for the scoring metric, hence a material co-produced will have a higher potential for disruption (because it is partially reliant on the production demand of another material) than a material produced without co-production.

To arrive at a score for PSD, it is proposed that scores for concentration of supply using the Herfindahl–Hirschman Index (HHI), Environmental constraints or contraction (ECR) and companion fraction (CF) are averaged. This is because they each represent factors that contribute to potential for supply disruption. At present, each additive factor is equally weighted so that the calculated value for PSD varies from 0 to 1. There is no evidence at present to suggest that any of the factors should have more or less weight than the others. PSD is expressed as follows, for material, m , where the weighting factor, k , is one third:

$$PSD_m = kHHI_m + kECR_m + kCF_m$$

2.3 Exposure to Supply Disruption metric (ESD)

The ESD metrics refer to characteristics of the Highways Agency's use of the material. ESD metrics rely on data gathered from the Highways Agency and professional judgement. Professional judgement would be sought, for example, from the owners of technical standards relating to a specific asset type.

The two sensitivity metrics which contribute to ESD are; asset sensitivity (AS) measures the extent to which an asset is reliant on the material, and function sensitivity (FS) measures the extent to which a function is reliant on an asset. This is primarily based on goal sensitivity (how important is the

asset to the overall goal or function) and price sensitivity (what proportion of the price of a technology is associated with the critical material in question).

For simplicity, it is proposed that a basic four level scoring approach is used for these metrics based on consultation with the Highways Agency and professional judgement. Table 1 summarises the scoring system used for ESD metrics.

Table 1: Scoring system for ESD metrics

ESD scores	Asset sensitivity (AS)	Function sensitivity (FS)
N/A	Material is not used to provide the asset.	Asset does not provide the core function.
0	Material is used to provide the asset; however multiple options are available – the asset is not sensitive to the material.	Asset aids the provision of the core function; however, it is not critical if removed.
0.5	Material is used to provide the asset with only few alternative materials available.	Asset contributes to providing the core function, but is supported by other assets.
1	Material is the only option to provide the asset.	Asset is critical to the provision of this core function (cannot be replaced/ substituted).

Additional research is required to determine how price sensitivity can be incorporated into the ESD metric. There is potential to include consideration of price sensitivity in the scoring of asset sensitivity, based on the proportion of spend going on each material required to provide each asset. However, based on the data reviewed by this project, a greater granularity of data is required than currently available (spend data reviewed is currently available by sub-asset category/ technology types rather than individual materials). At a higher level, spend data could inform the FS metric though analysis of the Highways Agency’s spend on asset types considering the functions they provide. This additional research would allow the quantification of this metric which would move beyond current estimation by professional judgement and provide further robustness to the framework.

It is proposed that the metric scores for Asset Sensitivity (AS) and Function Sensitivity (FS) are also equally weighted and combined so that ESD values are on a 0-1 scale. This is expressed as follows for material in function, mf , where weighting factor, k , is 0.5:

$$ESD_{mf} = kAS_{mf} + kFS_{mf}$$

2.4 Combination of the metrics

The two metrics, PSD and ESD, may be reported individually or combined (multiplied) into a single criticality measure (analogous to multiplying a probability and severity measure into a risk index). A simple indicative plot of PSD and ESD is shown in Figure 2 in the form of a risk matrix. The criticality scores for all materials providing a core function can be graphed to give an overall indication of criticality for a function.

When considering options for addressing criticality issues, either the PSD can be addressed, though substituting the material or changing the material specification or the ESD can be addressed, though making changes to how the core function is delivered by the assets as exemplified by the red arrows.

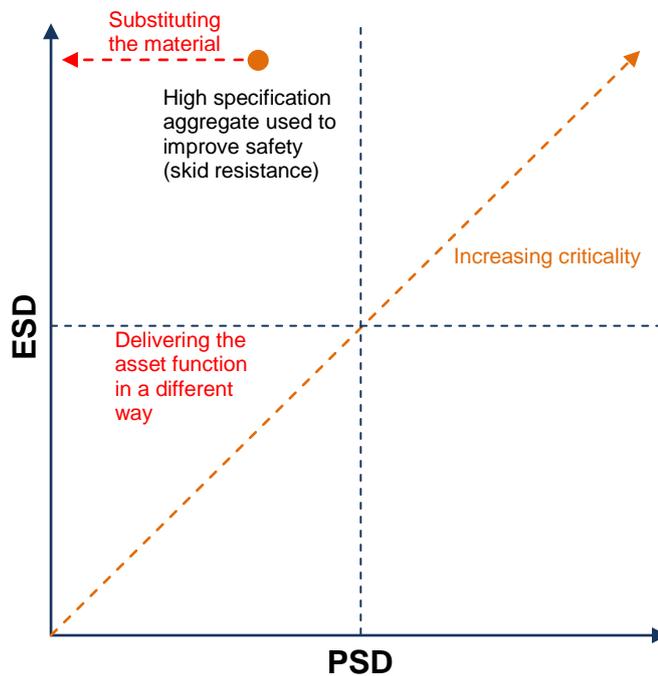


Figure 2: Criticality matrix

3 Highways Agency functions and materials

3.1 Identifying core functions

Assessment of material criticality is based on both a material's potential for supply disruption and the function's exposure to supply disruption. In order to assess the combined effect of these two issues, the Highways Agency's core functions have been mapped to the key materials which provide these functions (via their network of assets).

The term 'core function' is used to describe the key services provided (to the customer) by the Highways Agency asset. This is distinct from the core activities of the Highways Agency, summarised as operating, maintaining and improving the Strategic Road Network. A range of core functions were debated at the stakeholder workshop. It was agreed that for the purpose of assessing material criticality core functions needed to be defined independently of 'political' classification to ensure they reflected the practical service provision of the Highways Agency.

Based on the Highways Agency's mission statement of *safe roads, reliable journeys and informed travellers*, for the purpose of assessing a material's criticality to delivering the Highways Agency's core functions they have been listed as¹:

- Providing access and connectivity;
- Reliable journey times²;
- Safe roads;
- Providing information to road users; and
- Avoiding environmental impact.

These core functions are delivered through the range of activities undertaken by the Highways Agency and their delivery partners to operate, maintain and improve the asset.

3.2 Mapping materials to core functions

As a basis of the criticality assessment it is necessary to map the use of materials to the core functions they provide. The Highways Agency network assets provide the link between core functions and the materials used to provide those functions. The assets identified are listed below; these are informed by the Manual of Contract Documents for Highway Works (MCHW)

¹ Note, these core functions have been refined following feedback from the stakeholder workshop

² The three core functions, 'improving journey time reliability' 'tackling congestion' and 'managing traffic' have been combined as 'reliable journey times' following feedback from the workshop (27th February 2013, Lateral, Leeds).

and have been aligned to the asset types used in spend analysis undertaken by the Highways Agency:

- Pavements
- Drainage
- Earthworks
- Structures
- Restraint systems
- Markings and studs
- Traffic signs
- Traffic signals
- Lighting
- Soft estate
- Fencing

Each core function has been mapped back to the various Highways Agency assets which are required to deliver this function. Assets may be either crucial to deliver the core function or have a peripheral role in providing the function. Assets have subsequently been mapped to the materials they comprise.

Figure 3 presents this mapping exercise, illustrating the complex network of relationships between assets providing the various core functions of the Highways Agency and the materials currently used to provide those assets.

This mapping allows analysis to be undertaken on a section of this network, for example all the materials required to provide the core function of safe roads, or all the core functions provided by a single material, for example, copper.

In order to test the criticality framework, the project focused on two sections of the material-asset-function mapping, one to analyse for a single core function and one to analyse for a single material:

- Material case study: high-specification aggregates
- Core function case study: providing information to road users

Prioritisation of these two case studies was based on the workshop prioritisation exercise, a judgement of perceived potential for supply disruption based on work by the University of Leeds and availability of data necessary to complete the assessment framework.

The Highways Agency's high level of exposure to indigenous high-specification quarried aggregate material makes this case study of particular practical, academic and political interest.

The Highways Agency has expressed an interest in trying to determine the materials that are contained within 'black boxes' which are placed on the network. It is possible that some of the electronic devices placed on the network contain materials subject to high risk of supply disruption. The core function of providing information to road users relies upon such electronic devices. As identifying materials is only possible through talking to suppliers which was outside the scope of this project we have focused on copper as a material consumed in significant quantities on the Highways Agency network to provide electronic traffic signals and communications. Further research into these technologies is likely to be of great interest to a wide range of sectors as these devices and elements of the technologies are likely to be common to many sectors.

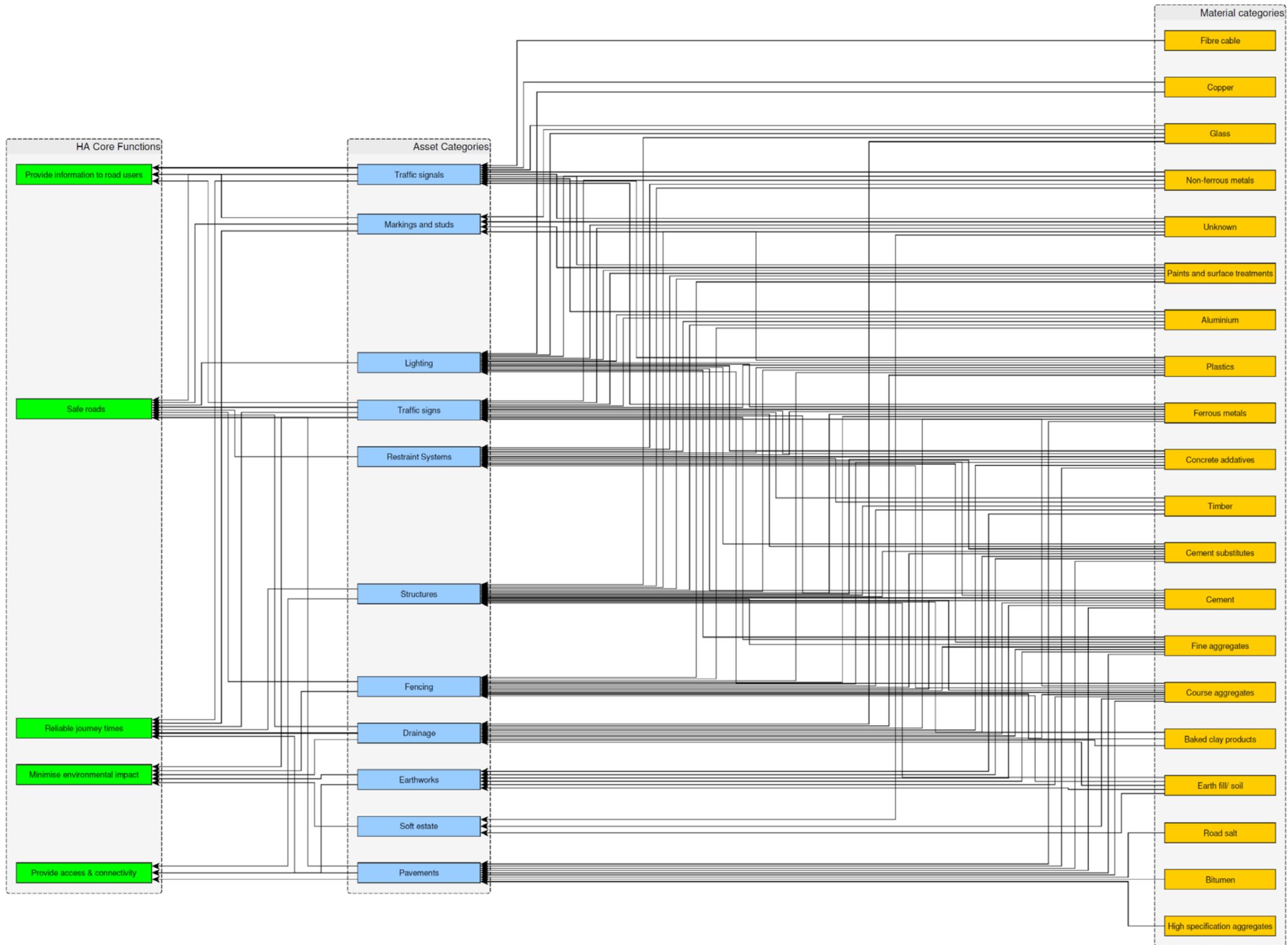


Figure 3: Example mapping of materials to Highways Agency core functions via assets (figure produced using yEd Graph Editor software)

4 Applying the criticality framework

This section describes how the criticality assessment framework developed for the Highways Agency as part of this project has been applied to two networks of materials, assets and core functions. Figures 4 and 5 illustrate these networks.

For each of these case studies the following sections attempt to apply the criticality framework for both the PSD and ESD metrics and combine these measures to provide an overall view of criticality.

4.1 Potential for supply disruption

Potential for supply disruption is measured using three variables as defined in Section 3 for each of the materials that have been mapped to Highways Agency assets.

Based on the Highways Agency supplier/project carbon returns data over three years, 75% of material consumption (by mass) on the Highways Agency network is quarry sourced material, either as aggregates, recycled aggregates or asphalt. Other notable material groups are concrete accounting for 7%, cabling (predominantly copper) at 4% and winter road salt at 5%. Table 2 shows the PSD metrics and combined PSD score. Figures have been provided by the University of Leeds; notes accompany some figures where they have been derived or assumptions applied. For figures presented in square brackets no data is available for the PSD metrics at this stage and so these figures have been estimated for the purpose of trialling the criticality assessment framework.

This long list indicates where data availability is generally good (for metals), where assumptions have been required to derive suitable PSD metrics, and where no data is currently available.

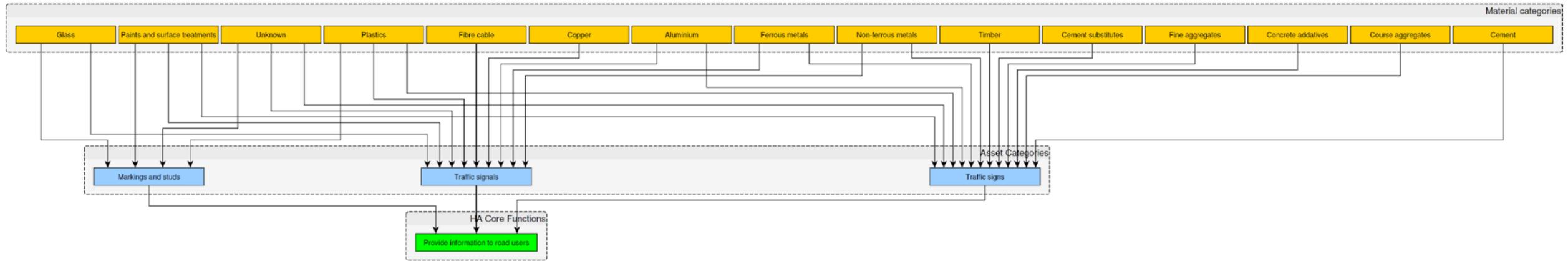


Figure 4: Core function – providing information to road users – asset and material network (figure produced using yEd Graph Editor software)

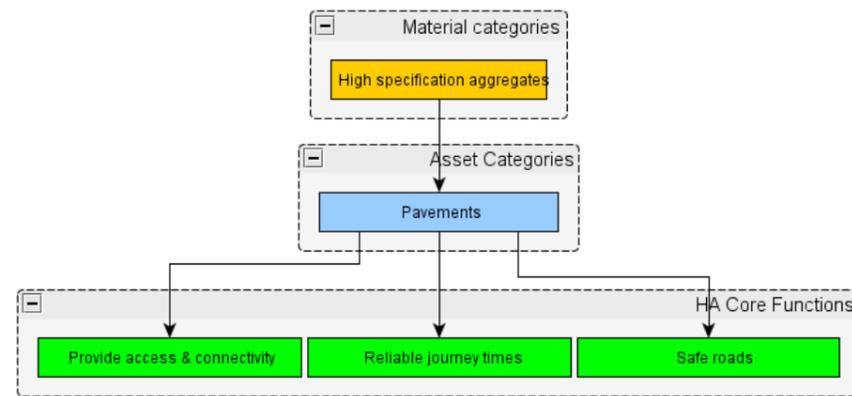


Figure 5: material – high specification aggregates – asset and core function network (figure produced using yEd Graph Editor software)

Table 2: PSD metrics

Material	HHI	ECR	CF	PSD
Coarse aggregates	0.200	0.688	0.10	0.33
High specification aggregates ^a	0.200	0.688	0.20	0.36
Fine aggregates	0.200	0.688	0.10	0.33
Bitumen	0.375 ^b	0.688	0.90	0.65
Cement	0.300 ^c	0.688	0.10	0.36
Cement substitutes	0.500 ^d	0.688	1.00 ^e	0.73
Concrete additives	[0.100]	[0.688]	[0.00]	[0.26]
Copper ^f	0.142	0.628	0.21	0.33
Aluminium	0.171	0.496	0.00	0.22
Ferrous metals	0.237	0.518	0.00	0.25
Other non-ferrous metals ^g	0.095	0.455	0.18	0.24
Fibre cable	0.100 ^h	0.688	0.50 ⁱ	0.43
Plastics	0.100 ^j	0.688	0.90 ^k	0.56
Baked clay products	0.100 ^m	0.400 ^l	0.40 ⁿ	0.30
Earth fill/ soil	0.100 ^o	0.688	0.20 ^p	0.33
Paints and surface treatments	[0.100]	[0.688]	[0.00]	[0.26]
Timber	[0.100]	[0.688]	[0.00]	[0.26]
Glass	[0.100]	[0.688]	[0.00]	[0.26]
Road salt	0.500 ^q	0.688	0.10	0.43
Unknown	1.000	1.000	1.00	1.00

^a Based on analysis undertaken as part of this project

^b Based on three suppliers: Nynas (2 plants), Shell (1), Total(1).

^c Based on four suppliers: Cemex 0.2, Heidleberg 0.3, Lafarge 0.4, Tarmac 0.1

^d Based on GGBS, only two steel suppliers in the UK

^e Solely a product of steel making

^f UI Project – University of Leeds analysis

^g values for Nickel used

^h No data available but appears to be a well developed market

ⁱ Uses some rare metals

^j well developed market, although some specialist materials may be difficult to obtain data for

^k By-product of oil refining

^l supply varied in the UK and internationally

^m from EC report

ⁿ 60% used for ceramics

^o estimated based on widespread availability

^p Generally leftover from cut/fill so difficult to assign a value to

^q two main suppliers in the UK – Salt Union and Cleveland Potash

[] no data is available for the PSD metrics, figures estimated to enable trialling the criticality assessment framework

4.2 Exposure to supply disruption

Exposure to supply disruption is measured using two variables – the sensitivity of the function to the assets providing that function and the sensitivity of the assets to the materials that provide those assets. The two ESD metrics are scored on a 0/0.5/1 scale as outlined in Section 2, each connection on the material mapping model shown in Figure 1 has been assigned a preliminary score on this basis in order to test the framework, this analysis is presented in Appendix A. Table 3 summarises the scoring system used for the ESD metrics.

Two case study examples have been used to explore the scoring of the ESD metrics which are described in the following sections.

4.2.1 Applying the framework for the core function: provide information to road users

Figure 4 shows that a wide range of materials are required to deliver the core function of providing information to road users. When assessing the sensitivity of the asset to the materials they comprise and the functions to the assets that provide them a 0/0.5/1 scale has been used. Table 3 shows the Asset Sensitivity (AS) and Function Sensitivity (FS) scores assigned to the materials required to provide information to road users (materials not required which would be scored N/A have been excluded from the analysis). These scores are based on an initial judgement by the project team in order to test the criticality framework. The scores can be refined based on professional judgement by relevant Highways Agency staff or potentially from material consumption or financial data.

The overall ESD score for a material to function chain is derived by taking the average of the asset sensitivity and function sensitivity scores. For example, aluminium contributes to providing information to road users via two assets – traffic signs and traffic signals. For traffic signals a 0.5 AS score has been assigned, whilst for traffic signs the AS score is 1. For both signs and signals the FS score is 1. Therefore the overall ESD metric for aluminium providing information to road users is 0.875.

$$ESD = \text{Average} (kAS_{mf} + kFS_{mf})$$

$$0.5 (k) * 0.5 (AS \text{ aluminium - signs}) + 0.5 (k) * 1 (FS \text{ signs – info to road users}) = 0.75$$

$$0.5 (k) * 1 (AS \text{ aluminium - signals}) + 0.5 (k) * 1 (FS \text{ signs – info to road users}) = 1$$

$$ESD = \text{Average} (0.75 + 1) = \mathbf{0.875}$$

Table 3: ESD metrics for core function – providing information to road users

Materials	Asset sensitivity to material (AS)	Asset	Function to sensitivity to asset (FS)	Core function
Copper	1	Traffic signals	1	Provide information to road users
Aluminium	0.5			
Ferrous metals	0.5			
Non-ferrous metals	1			
Fibre cable	1			
Plastics	0.5			
Paints and surface treatments	0			
Glass	0			
Unknown	1			
Coarse aggregates	0.5	Traffic signs	1	
Fine aggregates	0.5			
Cement	0.5			
Cement substitutes	0			
Concrete additives	0			
Aluminium	1			
Ferrous metals	0.5			
Other non-ferrous metals	0			
Plastics	1			
Paints and surface treatments	0			
Timber	0			
Unknown	1			
Plastics	1	Markings and studs	1	
Paints and surface treatments	1			
Glass	1			
Unknown	1			

The asset sensitivity metric can be considered to be a largely factual score based on whether a material is required to provide an asset and the importance of the material in the asset provision. Highways Agency

standards such as DMRB can be used to determine the AS scores based on the required standards and permitted materials for specific assets.

Function sensitivity is a more subjective metric which will require professional judgement by Highways Agency staff to determine the appropriate score.

The ‘unknown’ materials represent a significant level of uncertainty in the criticality framework and an area for further research to identify these materials where they contribute to various assets and quantify the PSD metrics for these materials. As a default the PSD score is set to 1 for the unknown material category to reflect the potential risk associated with this uncertainty.

4.2.2 Applying the framework for the material: high specification aggregates

High specification aggregates³ are solely used in the pavement surface course to provide the required levels of grip to meet safety standards. Figure 5 shows that pavements contribute to three core functions; providing access and connectivity, reliable journey times and safe roads. High specification aggregates have been assigned an AS score of 1 as the current standards for skid resistance cannot be provided without the use of these aggregates. Pavements have a FS score of 1 for both providing access and connectivity and safe roads and a score of 0.5 for reliable journey times. This results in an overall ESD score of 1 for both chains: high specification aggregates to providing access and connectivity; and high specification aggregates to providing safe roads. An ESD score of 0.75 has been calculated for high specification aggregates providing reliable journey times.

Table 4: ESD metrics for high specification aggregates

Materials	Asset sensitivity to material (AS)	Asset	Function to sensitivity to asset (FS)	Core functions
High specification aggregates	1	Pavement	1	Providing access and connectivity
			0.5	Reliable journey times
			1	Safe roads

³ High specification aggregates considered by this report are defined as those indigenously sourced with a high Polished Stone Value (PSV). Imported sources such as calcined bauxite, a synthetic aggregate, are not considered. Whilst calcined bauxite is potentially high-cost, it is an option that can provide the required function and diversify supply. This, and other ‘alternative’ materials, should be included for a full application of the framework.

The resulting ESD scores may indicate the need to refine the criticality assessment framework as high specification aggregates have a very specific function in providing a specified level of skid resistance for road safety. Therefore the ESD score of 1 relating to road safety can be expected, however, a score of 1 for providing access and connectivity is not necessarily accurate.

There are a number of considerations to be taken into account to address this. An option would be to consider a sub-set of asset properties rather than the asset as a whole. For example, for pavements, a sub-set of practical functions such as skid resistance, a smooth running surface and the network of interconnected roads could be considered in place of the single asset. Considering this sub-set could result in significantly different scores for both the AS and FS metrics. Table 5 shows an example of how the AS and FS metrics could vary if asset sub-function categories were used in place of the single asset type to derive ESD scores.

Table 5: Example ESD metrics for high specification aggregates with expanded asset categories

Materials	Asset sensitivity to material (AS)	Asset (sub-functions)	Function to sensitivity to asset (FS)	Core functions
High specification aggregates	1	Pavement – skid resistance	N/A	Providing access and connectivity
			0	Reliable journey times
			1	Safe roads
	0	Pavement – smooth running surface	0.5	Providing access and connectivity
			1	Reliable journey times
			0	Safe roads
	0	Pavement – interconnected road network	1	Providing access and connectivity
			0.5	Reliable journey times
			N/A	Safe roads

The revised ESD scores using asset sub-functions are presented in Table 6. Using an average of AS and FS to calculate the ESD whilst the ESD values for high specification aggregates are lowered for both providing access and connectivity and reliable journey times as expected the ESD score for providing safe roads is also lowered to 0.5 which would not seem representative of the criticality of this material to the function. This is due to

the score being ‘diluted’ by high specification aggregates also having a minor and substitutable contribution to providing other elements of the pavement asset (other than the skid resistance property).

An option to overcome this would be to use a worst-case scenario to determine the ESD score rather than an average. This would result in a maximum ESD score of 1 for high specification aggregates providing road safety and lower ESD scores of 0.5 for the other two core functions provided by the pavement asset.

Table 6: Example revised ESD scores based on expanded asset categories

Material	Function	New ESD (average)	New ESD (worst-case)	Previous ESD
High specification aggregates	Providing access and connectivity	0.38	0.5	1
	Reliable journey times	0.42	0.5	0.75
	Safe roads	0.5	1	1

Further investigation using a wider set of materials, assets and core functions is required to determine the most appropriate method of deriving ESD scores. The scoring scale would benefit from further research and analysis to determine the appropriateness of using a zero score for low asset and function sensitivity making up the ESD metric. Consideration should be given to using a 0.1 score to improve the ‘reliability’ of the framework.

4.3 Combining PSD and ESD scores

PSD and ESD scores can be combined to provide an overall view of criticality for a given core function of the Highways Agency.

The PSD scores presented in Table 1 and the ESD metrics in Table 3 have been combined (multiplied) resulting in a single criticality metric. These metrics are presented in Figure 6 as a summary of the criticality of materials for the core function of providing information to road users. For a single core function Figure 6 shows an example of how criticality can be considered in terms of the range of materials contributing to providing a function and the relative criticality of each material.

Figure 7 presents an alternative method of illustrating these combined criticality metrics for all materials. For each material used by the Highways Agency this graph shows how the combined criticality can be illustrated for each of the core functions.

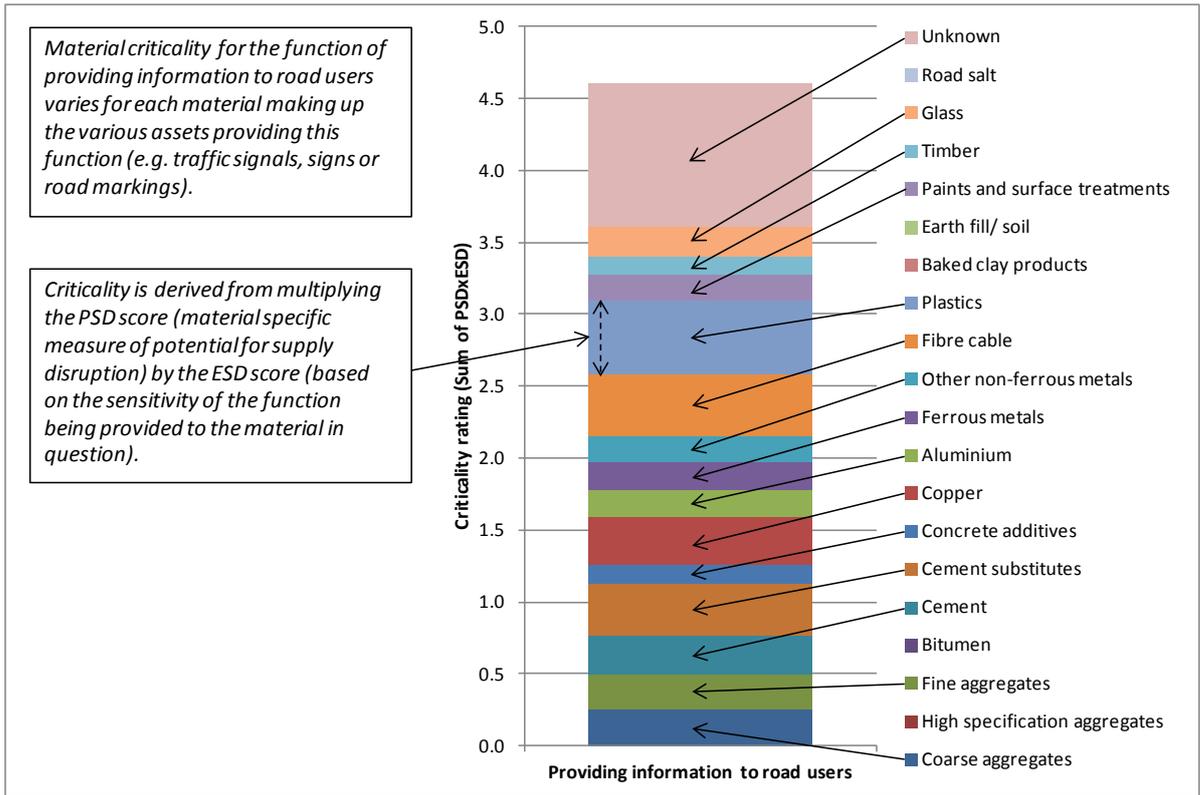


Figure 6: Example of combined criticality score for the function providing information to road users

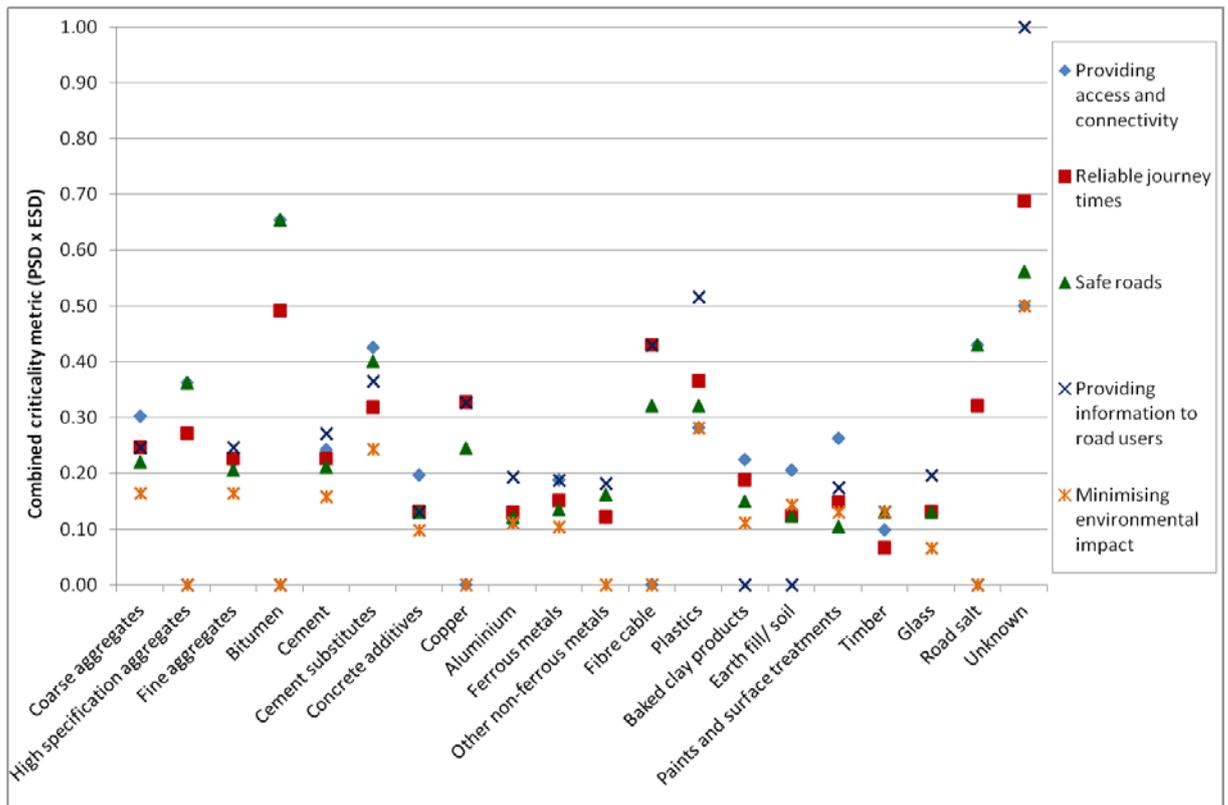


Figure 7: Example of presentation of the combined criticality metric

Each material contributing to providing the core function will have an overall criticality score based on its potential for supply disruption (measured by the PSD metric) and the sensitivity of the function being provided to the material providing it via one or more assets. The most critical materials will be those with both a high potential to experience supply disruption and for which the function is highly sensitive. This distribution of criticality risk can be illustrated on a matrix; for both case study examples the distribution of criticality scores is illustrated in Figure 8.

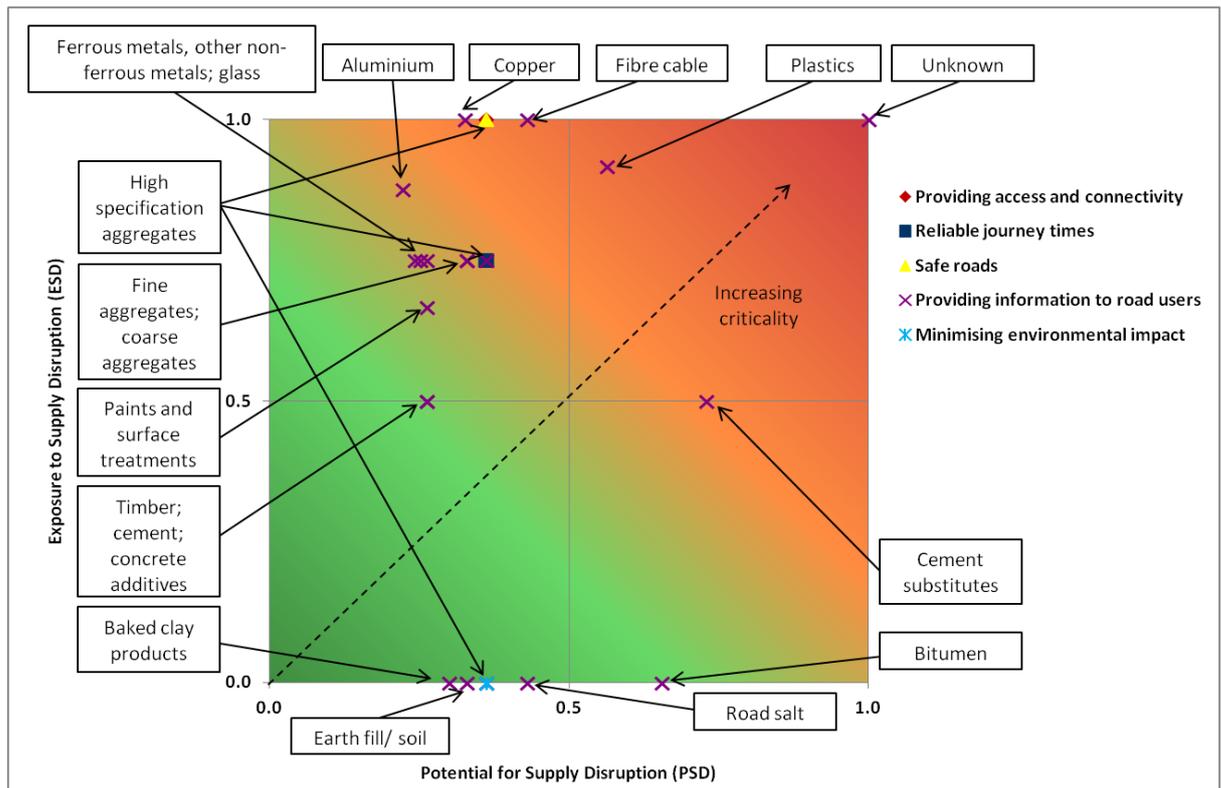


Figure 8: Example distribution of criticality scores for the function providing information to road users and the material high specification aggregates

Figure 8 provides a greater level of detail in defining the overall criticality scores illustrated in Figure 6. For example, both cement substitutes and copper have very similar criticality scores for the core function of providing information to road users. However, this is due to different factors. Copper with a combined criticality score of 0.33 is due to a high ESD (of 1), whilst cement substitutes with a criticality score of 0.36 is due to a higher PSD (of 0.73) but an ESD of only 0.5. This has significant implications when considering management or mitigation options to address potential criticality issues.

Considering the example of bitumen, whilst it has a relatively high PSD (of 0.65) it has an overall zero criticality score for providing information to road users as it does not contribute to any assets providing these functions. However, when considering other functions, for example, providing access and connectivity, ESD can be expected to increase and with it overall criticality for that function.

Based on the PSD scores presented in Table 1 and the ESD metrics in Appendix A, Figure 9 presents a summary of the overall criticality framework results. For each material to function, the PSD and ESD scores have been multiplied and summed for all materials critical to providing the function. For each material to function link the criticality rating ranges between 0 and 1.

The overall size of the bars gives an indication of criticality for each of the core functions, indicating that minimising environmental impact is the least critical and reliable journey times and safety are the most critical.

The distribution of PSD and ESD criticality scores is shown in Figure 10 for all materials and functions.

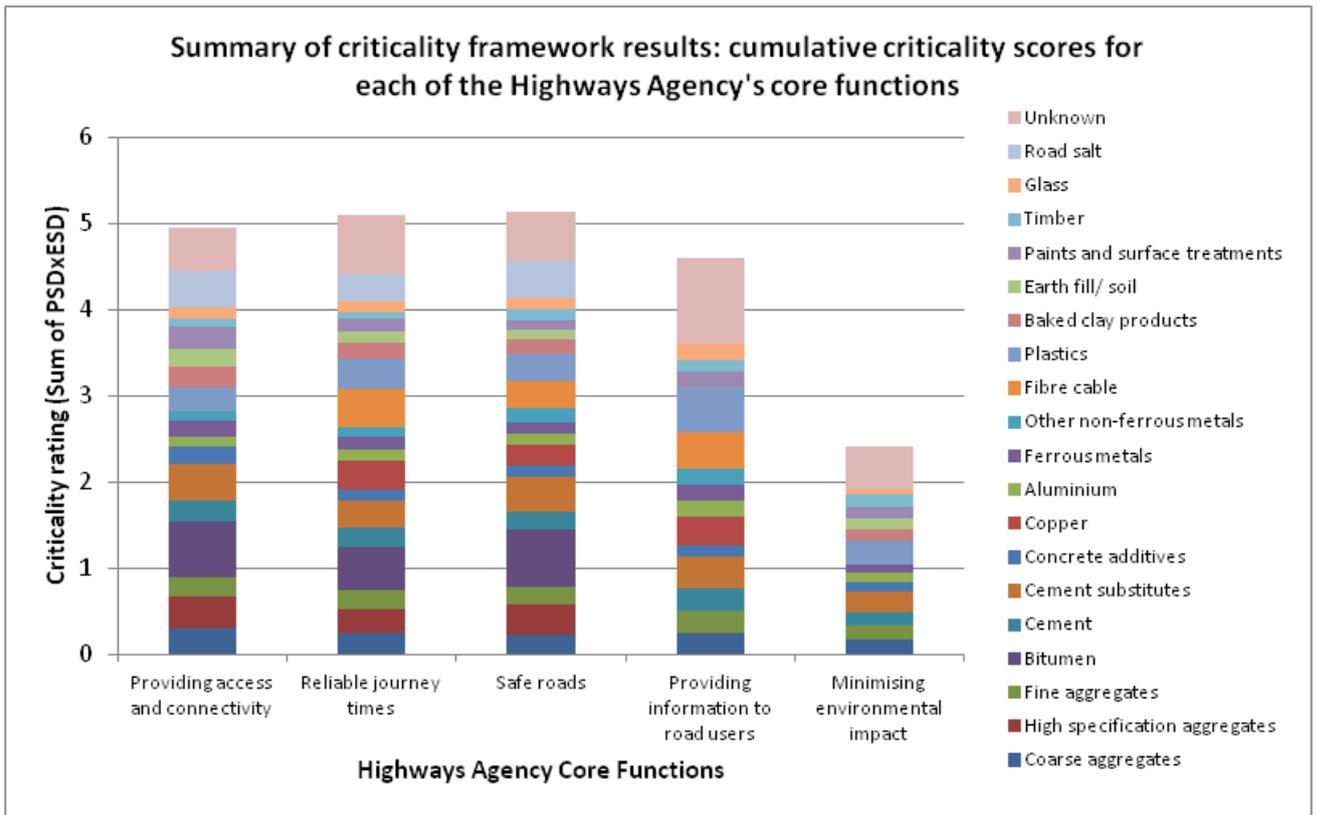


Figure 9: Summary of criticality framework results

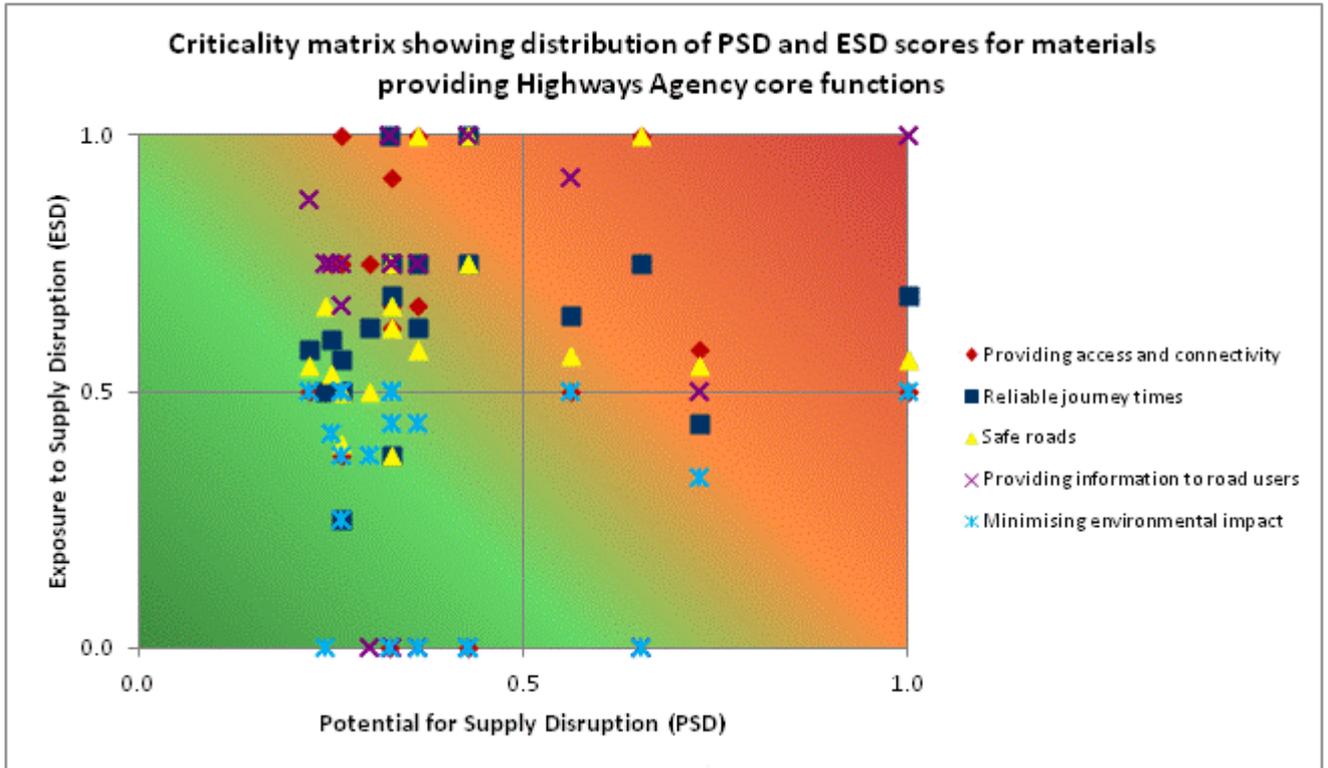


Figure 10: Distribution matrix of criticality scores

5 Current perceptions and considerations of material criticality in the Highways Agency

Two consultation activities were undertaken as part of this project: a broad online survey to gather information and perceptions on material supply risk across the Highways Agency and its delivery partners; and interviews focusing on individual asset types and materials. The consultation exercise was intended to gain an understanding of if and how material criticality issues are currently considered by the Highways Agency. The following chapter presents the findings of the consultation and discusses if and how criticality issues are currently considered by the Highways Agency.

5.1 Aims and objective

An online survey and questionnaire was used to investigate current perceptions of material supply risk and to understand existing methods used by the Highways Agency and delivery partners to manage supply risk. The following topics were of interest for the consultation:

- Approaches to managing general supply risks and performance (i.e. how do Highways Agency and its delivery partners ensure their supply is meeting standards and presenting risk to services/reputation/performance)
- Roles and responsibilities for managing material supply risk (i.e. who is responsible for ensuring security of supply? Should it sit entirely with the client?)
- Perceptions of Highways Agency staff and delivery partners of material supply risk, now and in the future
- Examples of materials and functions that might be particularly at risk or vulnerable
- Examples of supply disruption events
- Ideas for ways in which risks posed by the potential for material supply disruption can be managed and mitigated

The consultation was aimed at both HA staff with responsibility for procurement and at delivery partners. A full list of questions is shown in Appendix B.

5.2 Survey sample

The online survey was distributed to a targeted group of 58 Highways Agency staff covering a broad range of responsibilities in the Agency including for the various asset types, standards, procurement across the various contract types, Major Projects, NetServ and NDD Divisional Directors. In addition to the internal Highways Agency target audience, the survey was also directed at Managed Motorways Delivery Hub partners.

A total of 36 respondents completed the questionnaire, which was open for responses for a period of six weeks. 32 of the respondents were from the Highways Agency with 4 responding from HUB delivery partner organisations. Responses were received across the range of target divisions of the Highways Agency. Of the 36 people who started the survey, 25 gave complete responses.

Additionally a number of follow up interviews were made with Highways Agency staff to obtain further detail on specific materials and assets or from commercial perspectives.

5.3 Management of material supply risks

5.3.1 Importance of supply risk in decision making

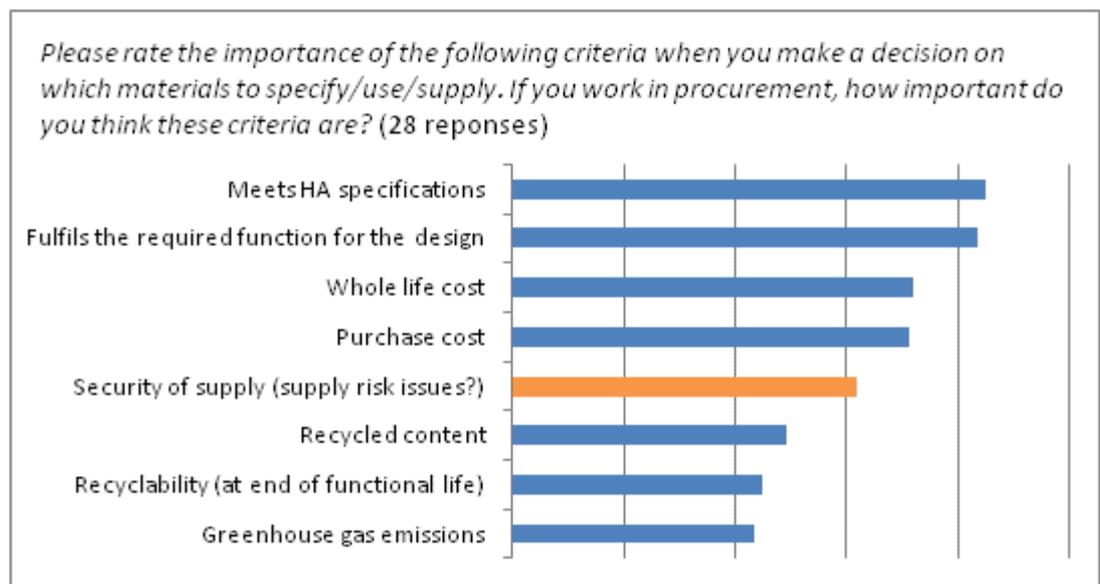


Figure 11: Ranking of decision making criteria for material specification

Respondents to the online survey were asked to rate the importance of a range of criteria relevant to various financial, quality and environmental risks in decision making on material specification on a five point scale from 'never considered' to 'always considered' (in decision making) with a sixth 'Don't know/ not applicable' option.

The results, illustrated in Figure 11, show that security of supply is rated as having medium importance relative to other criteria with only specifications, meeting functional requirements and cost being rated of higher importance. Whilst five respondents answered 'don't know' six and ten answered 'always considered' or 'often considered' respectively (57% of those providing a rated response), indicating security of supply is an issue currently considered in decision making but not in all circumstances.

It can be expected that meeting the necessary specification and fulfilling the functional requirements of the design (engineering 'quality' criteria) are both routinely considered and of high importance in decision making, to a certain

extent a pre-requisite for the options being considered. Cost is routinely cited as the most important decision making criteria, which is reflected in the survey responses. Security of supply is ranked as of higher importance in decision making than the three environmental 'quality' criteria listed. This indicates that whilst not a core consideration such as cost or engineering suitability, the ability to supply material is considered to some degree in the decision making process. The extent to which this is a long or short term consideration will be considered by other questions in this survey.

5.3.2 Processes to identify supply risks

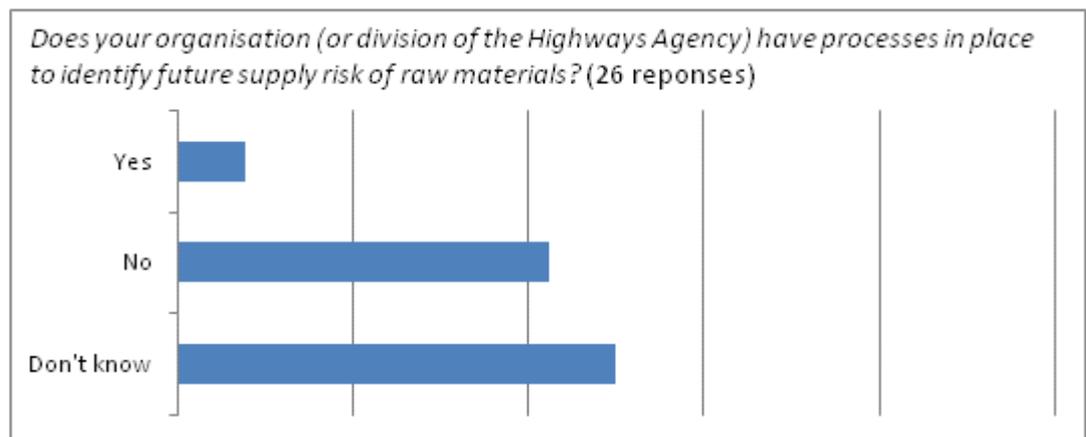


Figure 12: Processes in place to identify future supply risks for raw materials

The second question considers processes that the Highways Agency and their delivery partners have in place to consider the potential future supply risk of raw materials. The overwhelming majority of respondents to this question answered 'don't know' or 'no' with only two respondents answering 'yes'. The two positive responses came from Highway Agency delivery partners.

One of the respondents indicating that 'processes were in place', provided the additional supporting comment "[processes are in place] when [future supply risk of raw materials] is brought to our attention through a related action by others". The other respondent commented that processes were in place, but only for key products they use all the time, for example asphalt, and that pressure is principally from the client.

This indicates that future supply risks of raw materials are not considered directly by the Highways Agency, passing consideration of this risk to their supply chain. Whilst two delivery partner responses indicate that the risk of future supply disruption is considered, the supporting commentary suggests that this is through reactive rather than proactive risk management. However, a greater sample size of delivery partners and more detailed consultation would be required to confirm this.

5.3.3 Processes to ensure access to raw materials

The survey asked respondents how they (and their organisations) ensure that they have sufficient access to raw materials to deliver their operations now and in the future. Of the 26 responses a wide range of comments were received, these have been broadly categorised into the four sections below.

5.3.3.1 Reliance on suppliers

Four responses were given from Highways Agency respondents that they rely on their service providers to ensure sufficient raw materials for their operations.

In the electronic signals, lighting and signs sector the Highways Agency purchase equipment as commodities on the open market rather than setting design standards. Whilst this does not remove the risk of supply disruption causing an issue for the continued operation of the Highways Agency network it has placed consideration of this risk with the suppliers (if considered at all).

Responses' indicating that reliance is placed on suppliers to ensure access to sufficient raw materials all appear to focus on short term supply rather than long term potential supply risks. One response suggested raising an early warning to alert the Highways Agency overseeing organisation as the mechanism to raise any issues.

5.3.3.2 Working with suppliers

A further four responses focused on working with suppliers to ensure sufficient access to raw materials. This is achieved through involving suppliers in developing the forward programme of work and reviewing supply risk. The Highways Agency is already in contact with key suppliers to review risks, for example salt suppliers and steel suppliers.

A specific example for steelwork was provided where the Principal Structures Advisor has six monthly meetings with the steel bridge industry at which supply issues are discussed; any issues can subsequently be fed back to the Agency.

This indicates that for certain key materials, possibly as a result of previous supply disruption incidents, systems are in place to consider, manage and mitigate any potential supply risks. Further consultation is required to assess at what level these risks are managed; who holds the responsibility for this risk management and whether methods and lessons are shared across divisions of the Agency and their suppliers.

The responses from three delivery partners provide limited evidence that material supply issues are considered proactively. The responses indicate that the availability of materials may be considered during design as one of a range of issues when considering the feasibility of solutions. However, this is likely to result from the issue being brought to the designers attention by the action of others rather than proactive processes.

5.3.3.3 Specific design/specifications/targeted interventions

In certain circumstances, specific examples were cited where the Highways Agency has taken measures to ensure the ongoing supply of materials. The example of management of the strategic salt supply was given, with stock piling additional supplies as emergency cover used to mitigate supply risk.

Promoting the use of recycled materials and design alignment to achieve a balance between cut and fill materials is cited as a measure used that helps ensure the security of supply for key aggregate construction materials. This is also driven by other environmental drivers such as carbon and resource efficiency considerations as well as potential cost savings.

5.3.3.4 Issue not considered, not considered an issue or not known

Five responses suggest that the security of material supply is not currently considered for various reasons. Two cite that they assume the advancement of technology may mean that the materials currently being used on the Highways Agency network may not be the same as those in the future, and therefore a long term view is not taken. The specific example of using cut and fill to supply materials for new works and reinforcing earth are two 'technologies' that are recent 'innovations' to supply materials for earthworks.

A further response suggests that as material criticality has not been identified as an issue it is not something that is currently considered. This is supported by examples of where criticality has been considered in some way, for example for salt and steelwork, which have been reactive to supply disruption incidents.

Interestingly one response from a delivery partner also states that they have not considered this as an issue except one specific occasion when it was highlighted in advance. This suggests that despite a number of Highways Agency responses indicating that security of supply is not routinely considered by the Agency or that reliance is put upon supplier, delivery partner organisations may not be proactively managing the risks. However, as previously stated, a larger sample size and further consultation of delivery partners and supplier organisations is needed to confirm this.

Finally five respondents answered that they did not know whether access to raw materials is considered or that it is not part of their role.

5.4 Perceptions of Highways Agency staff and delivery partners of material supply risk, now and in the future

5.4.1 Level of concern over the immediate and short-term availability of key materials

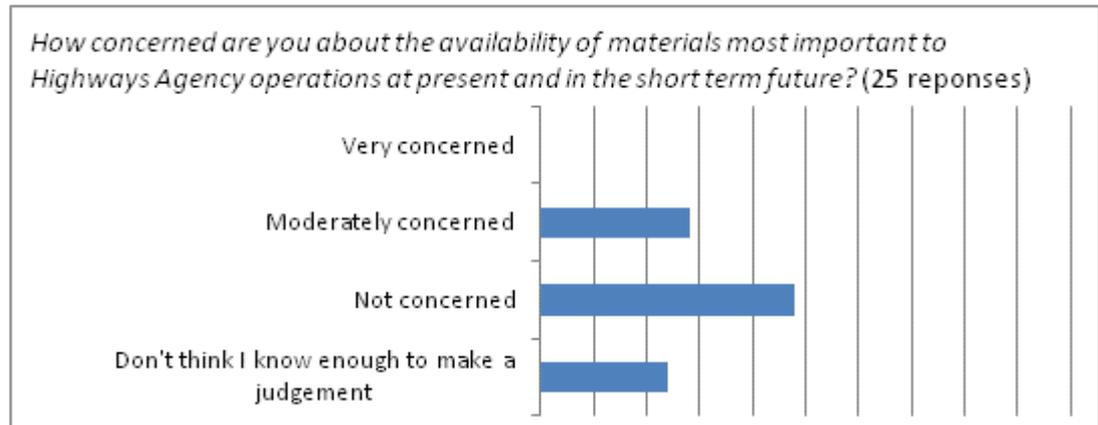


Figure 13: Immediate and short-term level of concern over material availability

The responses to this question indicate that the majority of respondents are not concerned about the present and short term availability of materials with a significant minority not feeling able to make a judgement. No respondents answered that they were very concerned, reflecting that the Highways Agency has not suffered significant issues with the supply of materials that could not be overcome. However, seven respondents (28%) indicated that they were moderately concerned.

Three cited separate issues related to the electronics industry as a cause for concern; one relating to material availability around electronic circuit boards and wiring and two indirectly related issues of copper cable theft (induced in part by the high price commanded by copper as demand exceeds supply), and the commercial stability of the few small companies relied upon to supply technology equipment.

One respondent cited concern over the ability for supply to meet the demand that will be created by the significant (politically induced?) workload over the next three years with a significant programme of highway construction and maintenance.

The long term supply of bitumen is raised as a potential concern, having once been the waste element from the oil industry supply is continually reducing as the ability to obtain more lucrative products from lower grade oil increases. The highways industry only has limited leverage with the oil industry due to their [oil industry's] customer base and limited requirements of the highways industry and hence emphasis is needed to consider alternative materials as binder products.

Of the respondents answering not concerned two provided additional commentary to support their answers. The first raised the issue of rising price as the main concern rather than the ability to obtain the necessary materials. Whilst deposits of materials continue to be available as they become less accessible to mine commodity prices increase. Criticality issues with reference to earthworks materials are not expected to be an issue due to the ability to use site-won materials and in most scenarios their design can be adapted to suit site conditions.

5.4.2 Level of concern over the medium and long-term availability of key materials

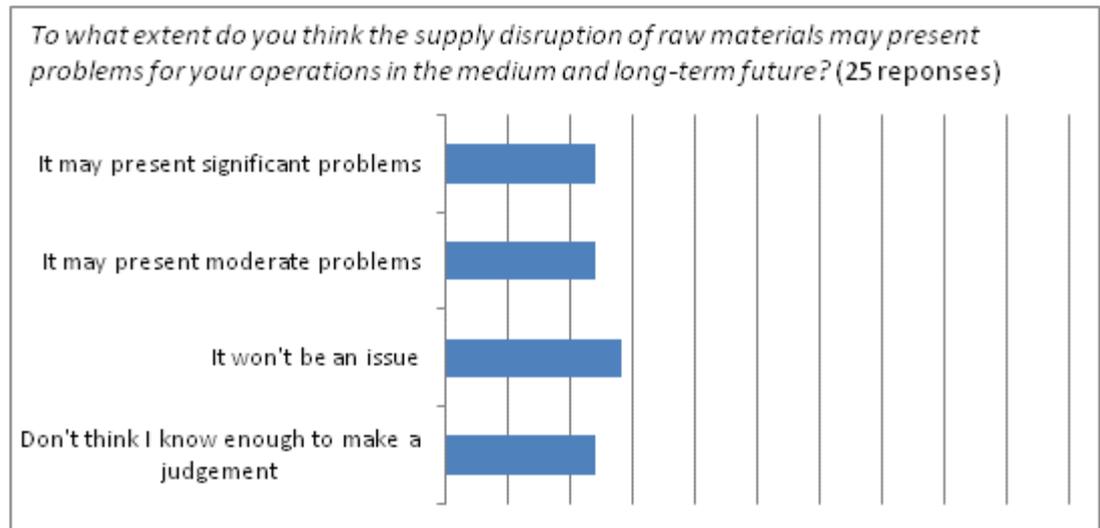


Figure 14: Medium and long-term level of concern over material availability

The responses to this question have clearly split opinion with 48% of respondents expecting that supply disruption of raw materials may present moderate or significant problems in the medium or long-term future, 28% expecting no issues and a further 24% considering they do not know enough to make a judgement. This may reflect the earlier finding that supply disruption is not routinely considered by the Highways Agency for all materials and hence a certain level of uncertainty can be expected over any potential medium and long term problems.

Of the supporting comments a number of potential problems and concerns were highlighted. Bitumen, premium aggregates, copper, LEDs are highlighted as of particular concern in the medium and longer-term. Current market trends suggest that the supply of structural grades of steel should not be a problem; however, global economic trends may impact on this. Economic factors are highlighted as an area of medium to long-term concern when considering the impact of global economic recovery, geographical constraints on supply favouring emerging developing countries who may wish to serve domestic demand and the impact the 'futures' market may have on driving commodity prices.

There is a general trend that concerns are variable depending on the material in question. In certain cases material demand for the Highways Agency network may actually reduce as technologies become redundant or improvements in performance reduce material demand. For example, in car technology may significantly improve safety performance reducing the need for safety barriers.

5.5 Materials and Highways Agency functions that may be at risk from supply disruption

5.5.1 Materials used by the Highways Agency

Survey respondents were asked which materials they rely upon most for their operations. A long list of key materials was provided shown in Table 6.

Table 6: key materials for the Highways Agency network

Key materials for the Highways Agency network	
Bitumen	Cement
General aggregates	Oil based polymers for reinforcement
Premium aggregates	General fill
Electronic technologies (for communications, metals, plastics etc.)	Graded fill
Communications infrastructure (gantries, ducting, steel, plastics etc.)	Plastic pipes
Copper	Iron for surface drains
Stainless steel	Zinc dip coat to galvanise steel posts
LEDs	Aluminium to sign backing
Concrete pipework	Plastic coatings to posts
Salt	Rubber seals on electric cabinets
Structural steelwork	Some rare earth elements in electronic circuit boards
Steel corrosion protection coatings	Soils (usually site won)
Ferrous metals	Granular materials (for earthworks)
Non-ferrous metals	Limestone
Concrete	

These materials are consistent with those identified in the outline criticality framework presented in section 3.

5.5.2 Ability to substitute key materials

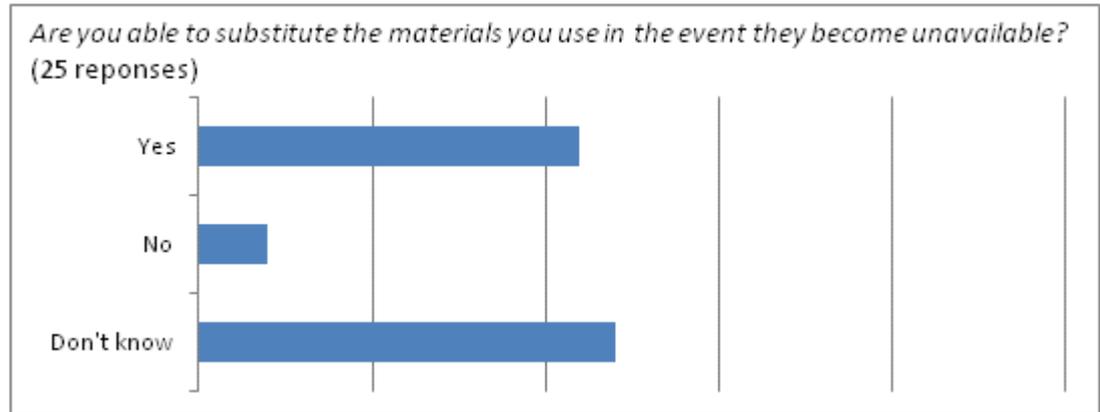


Figure 15: Ability to substitute key materials

For the materials listed, respondents were asked to consider whether they would be able to substitute them in the event that the material becomes unavailable. The responses to this question reflect the range of materials used on the Highways Agency network. 48% of respondents answered that the materials they use are substitutable; a number of examples were provided to illustrate potential options for substitution. For power distribution aluminium or stainless steel were highlighted as a potential substitute for copper, in addition to alternative power distribution designs to reduce the need for copper and utilise renewable energy technology. For drainage products a range of material types are already used to produce substitutable components reducing the risk for this asset type. Structural steelwork is generally seen as substitutable, and as highlighted in a previous question, not of concern for supply disruption. For earthworks and aggregate use materials are generally seen as substitutable through the greater use of recycled products, sourcing materials on-site and technologies such as soil stabilisation and other treatments.

Oil based products were highlighted by a number of respondents as difficult to substitute, in particular bitumen. Where potential substitutes for materials are available, cost and quality implications were anticipated. In many cases the use of an alternative material would require approval from the Department for Transport where the existing specifications do not have sufficient flexibility to accommodate their use.

5.5.3 Exposure of Highways Agency assets to materials not easily substitutable

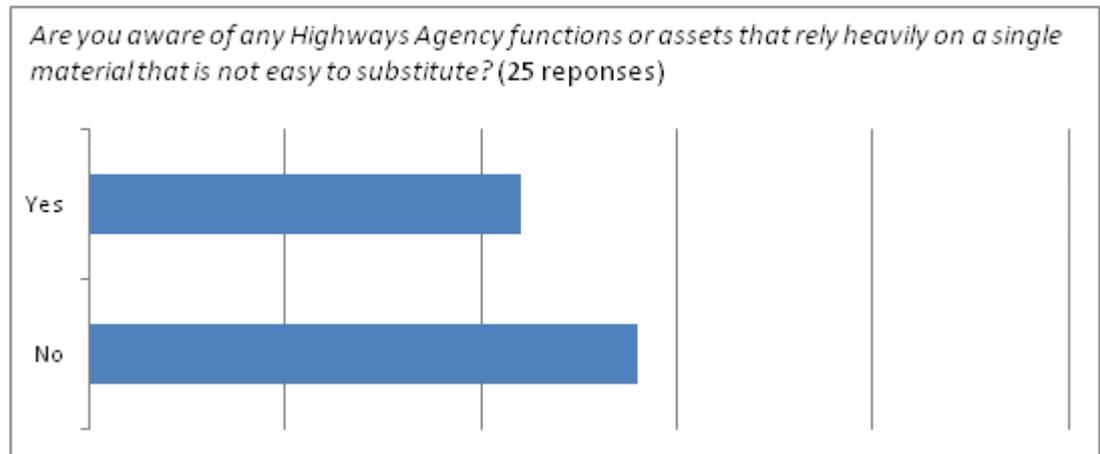


Figure 16: Exposure to materials not easily substitutable

When asked to consider whether the Highways Agency network is reliant on any materials which are not easily substitutable ten respondents answered 'yes'. Responses and supporting comments were, on the whole, consistent with the answers to previous questions, citing oil, bitumen and salt as materials of greatest concern. In addition copper was highlighted as difficult to substitute for power cables, although aluminium has been identified as a potential substitute in certain applications. 'Black box' technology assets were identified as a potential area for concern due to the uncertainty over what materials are contained within these assets.

5.5.4 Examples of supply disruption events with management and mitigation options to address risks

Table 7 summarises the range of responses citing materials that have experienced supply disruption events affecting the Highways Agency network.

Three respondents provided details for supply disruption of structural steelwork. A further three cited the example of disruption to the supply of salt for winter gritting in 2009/2010. The theft of copper cable was raised as having affected the Highways Agency network; however, details were not provided for this example.

Table 7: Examples of materials that have experienced supply disruption events, the impacts and lessons learnt

Material	Cause of supply disruption	Impact of supply disruption	Solution and lessons learnt
Steelwork	Specific grades of steel used for the construction of highway structures that can accommodate extreme low temperatures are only rolled at certain times of the year. Consequently demand for structural steel work can limit supply.	<ul style="list-style-type: none"> • Rising cost of steelwork. • Extended delivery times. • Inability to supply / deliver in accordance with ministerial commitments. • Attempts to use lower [building grade] steel which can become brittle at low temperatures. 	<ul style="list-style-type: none"> • Advance procurement / pre-ordering required to secure supply early in the design/construction process. • Low temperature testing required for steelwork to confirm adequate tolerance. • Cost implications recognised in contract valuations.
Salt	Local Highway Authorities relied on 'just in time' deliveries and due to exceptionally cold temperatures over a prolonged period demand exceeded the ability of suppliers to mine the salt. This led to Local Highway Authorities asking the Highways Agency to share the national over ground stocks, leading to a shortage in stock.	<ul style="list-style-type: none"> • Reduction in the ability to undertake salting operations. • Disruption to road users. • National concern about ability to keep roads free from ice. 	<ul style="list-style-type: none"> • The Highways Agency intervened and directed supplier deliveries at a national level. • Some additional supplies obtained from international sources. • Planning of salt stocks for future years to create additional strategic stockpiles, distribution and resource arrangements.
Wire rope for safety barriers	Instances have arisen when the Highways Agency has had insufficient spares for wire rope barrier and technology and their supplier have not had them in stock either.	<ul style="list-style-type: none"> • Unable to repair infrastructure. • Reduced service to consumer. 	<ul style="list-style-type: none"> • Mores spares are now kept

Material	Cause of supply disruption	Impact of supply disruption	Solution and lessons learnt
Road markings materials	Lack of availability of raw materials required for road markings	<ul style="list-style-type: none"> Unknown impact of disruption. 	<ul style="list-style-type: none"> There is a need to be aware of how the supply shortages of raw materials could affect construction and maintenance operations and have contingency plans in place, based on risks to the Agency, if appropriate.

5.6 Changing highways infrastructure and potential resulting future issues

The consultation exercise sought views on how highways infrastructure is changing and is expected to change in the future. The following sections discusses responses related to the increasing use of technology, changes to design and material specifications and changing approaches to asset management.

5.6.1 Technology on the Highways Agency network

It was commented that “the Highways Agency is becoming a technology business”. This is reflected more widely in the other responses to this question. The Highways Agency's role as an operator, rather than just a road builder, and the current restrictions on funding has meant that they are looking at ways to provide the service without having to provide more or wider roads. This has led to a shift in focus towards managing traffic though reliance on electronic technology rather than building more carriageway space.

Such technologies, including telemetry, variable signing/ signalling and CCTV, have led to an increase in small structures such as masts and gantries. However, the deployment of this technology has avoided widespread upgrading that would have been necessary if its absence. For smaller structures, like masts, there has been an increase in the use of aluminium and fibre-reinforced plastic (FRP). This is helping the Agency achieve improved asset use, making use of the existing network, with technology assisting in delivering the asset function to the required service level, for example though Managed Motorway schemes.

This current shift toward the utilisation of greater levels of technology on the network is not necessarily seen as a long term trend. It is anticipated that in-car technology is likely to surpass the current network level technology solutions potentially limiting the requirements for continued development and roll out of future infrastructure technology solutions. One respondent

commented that systems such as automatic driverless vehicles and universal satellite navigation means that the only requirement could be a surface to run on, all the information being relayed to the vehicle directly; thus no need for signage, lighting, road or lane markings or crash barriers.

Existing infrastructure is also changing to adopt more technologically advanced solutions. Whilst there is a general trend to light fewer roads, the infrastructure that exists to provide lighting is becoming more complex, driven by the need to reduce energy consumption. For example, traffic signals are required to be LED based and with low voltage controllers. Sensors are wirelessly operated and often powered via on-site micro-renewable generation, such as solar panels.

The Highways Agency procure communications equipment through provider NERT, this is as a service rather than a product and therefore the Highways Agency do not specify materials or products and have little knowledge of the materials required to provide the functions delivered by these assets. This has followed a general drive towards performance based specifications, rather than material specifications. Whilst this may remove certain elements of the financial and performance risk from the Highways Agency the exposure to potential supply disruption events still exists to the function provided by the asset.

Traditionally Highways Agency specifications have had a tendency to over-specify copper cables in setting their standards. The quantity of copper historically used on the Highways Agency network may present a future opportunity as this method of communication cabling is replaced by fibre or wireless technologies or the need for communications equipment is reduced as technology increasingly moves in-car.

When considering material criticality in the asset group of communications equipment, it is difficult to assess future risks posed by potential supply disruption due to the rapid evolution of communications technology. Technology assets installed tend to have a 15 year design life and require little planned maintenance. Beyond this timescale the next generation of technology assets may have a very different set of materials or method of delivering the functions required.

The technology systems currently being deployed on the network and the anticipated roll out of further technology assets are highlighted as a potential future risk where they rely on single or few supply sources. However, the respondent anticipates that inevitable cost increases for such materials are more easily absorbed due to the high value of Highways Agency assets than low value applications, such as budget mobile phones.

5.6.2 Design and material specifications

Various responses have indicated a shift in the way materials are used in designs, the specification of materials and the production methods for materials. Greater awareness of resource efficiency and carbon accounting has in part led to an increase in the use of recycled materials and site-won

materials for earthworks. One respondent noted that as technology becomes lighter and more compact there is a knock-on impact on supporting infrastructure. Another that there is now less infrastructure on the roads, particularly a reduction in street furniture.

A move to off-site production and prefabrication was noted shifting more work to factories and changing the way raw materials are used and on-site construction techniques.

A move by the Highways Agency to the use of performance based specifications has allowed a wider selection of materials in delivering its assets. The Agency is able to directly influence infrastructure and the materials used in it through its standards and specifications. For example, it has encouraged the use of weathering steel in bridges through a change in the headroom limitation it imposes through standard BD7.

The Highways Agency has been willing to consider the use of new materials, however, it does have to adopt a cautious approach given its responsibilities for safety on the network, getting value for money and the consequences of materials not performing as expected. However, this has not been without issues with the introduction of thin surfacing cited by two respondents as having caused problems due to not being as durable as previous materials, especially in cold weather conditions.

A concern was raised over the ability of Highways Agency specifications to keep pace with performance based requirements that are currently being introduced. Whilst performance based specifications allow for more flexibility in the use of materials, the Highways Agency will still require a rigorous performance testing process to demonstrate reliability, this can be a time consuming process.

5.6.3 Approaches to asset management

A number of comments were made about how the Highways Agency is changing its approach to managing the road network and how this will impact on the materials used. It is anticipated that financial pressures will lead to the asset being maintained in a targeted manner and lead to more patching on carriageways and more use of faster construction techniques such as cold laid ultra thin surfacing (CAUTS).

The way the Highways Agency maintains its assets has changed under the new Asset Support Contract with focus on interventions that provide for the longevity of the asset with move away from large scale projects. Aggregation of demand by procuring through the category management has enabled frameworks for a number of projects or maintenance requirements to achieve best value for the Agency.

5.6.4 Impact of rising energy costs

A number of responses focused on the impact that rising energy costs may have on both operating the network and the resultant rise in cost of raw

materials, such as bitumen. Whilst this may impact upon the future use of materials, for example, if micro generation becomes more common on the road network, at present supply issues have not been identified. The use of natural aggregates was highlighted as of potential concern as increasing attention is given to embodied carbon.

5.6.5 Understanding of supply chains for new materials and technologies

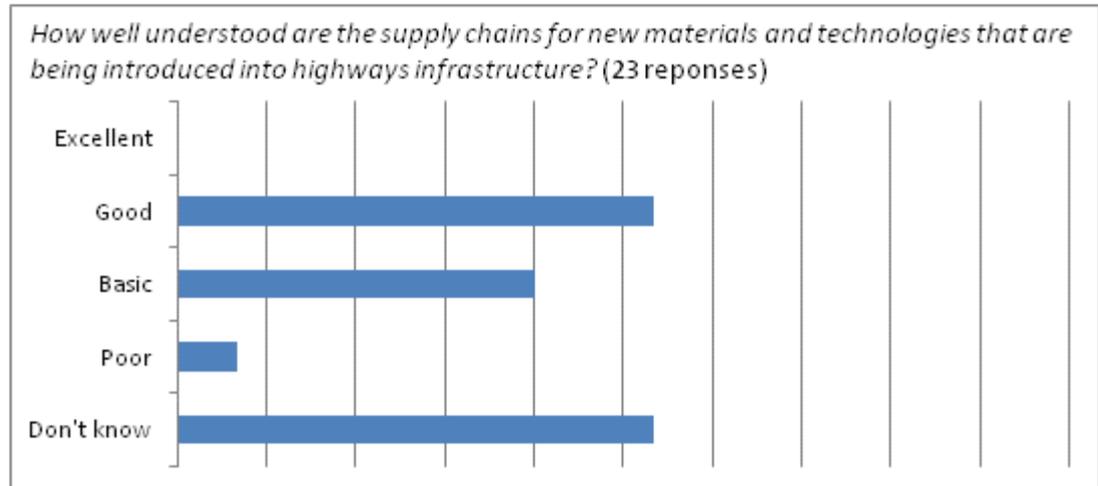


Figure 17: Understanding of supply chain for new materials and technologies

When asked how well understood the supply chains are for new materials and technologies responses are inconclusive, with a near equal split of opinion between those believing supply chains for new materials and technologies for highways infrastructure are well understood, and those believing they are only basically understood, with a further third responding 'don't know'. The high response rate for 'don't know' may also be indicative of the ambiguity of the term 'supply chain' in the question; for example, whether this refers to familiarity with the direct supplier or knowledge of the network of suppliers from source to delivery (whether currently used or not by the Highways Agency).

However, of those people who responded 'good' three qualified their answers to state the availability of, and supply chain for, any new materials would be one aspect that would be considered when consideration is being given to adopting a new material. This perhaps suggests that the respondents qualified to accurately answer this question have indicated that the Highways Agency does have a good understanding of the supply chains for new materials and technologies.

5.7 General comments on the survey

Of the respondents a high proportion did not fully complete the survey with one commenting that it was very difficult to complete. This may reflect that material criticality issues are not currently widely considered or understood by the Highways Agency or their immediate supply chain, or that some of the respondents were not the appropriate target sample for the survey. A

number of respondents felt the issues in question were not relevant to their role, despite having influence over the design or construction of projects and hence specification and use of materials.

There could also have been a tendency to skip rather than answer “no I don’t think there will be a problem” due to the open-ended nature of questions (as oppose to rating type multiple choice answers), the number of questions and a possible view that criticality is not an issue for the materials used or considered by respondents.

The overall sample size from Highways Agency staff was good with a response rate of 57% (32 out of 58 targeted respondents) but only a limited response was received from HUB delivery partners (4 responses) with no wider consultation undertaken with the Highways Agency suppliers.

6 Conclusions

- This project has developed a framework for considering material criticality through consideration of both a material's potential for supply disruption and a function's exposure to supply disruption. Combining the metrics provides an approach analogous to risk assessment. The framework builds upon the latest academic thinking from the University of Leeds UI project.
- Potential for supply disruption (PSD) is a property of the material. This can be readily quantified for metals and some other construction materials using existing data/ research. However, it is more difficult to quantify for non-metallic materials at the present time.
- Exposure to supply disruption (ESD) is specific to the way in which the Highways Agency uses materials in delivering their core functions. ESD is sensitive to the importance of the material in delivering a goal (core function) and the price sensitivity of the material in delivering an asset. Quantifying the ESD metric is currently a subjective measure. There is potential to use Highways Agency commercial/ material consumption data to significantly refine the quantification of this metric.
- To incorporate commercial data to ESD metrics, greater granularity of data is required than is currently available (spend data reviewed is currently available by sub-asset category/ technology types rather than individual materials).
- Linking materials to the core functions of the Highways Agency via the mapping exercise undertaken by this project is a new approach and allows modelling of criticality issues and application of the criticality framework.
- Clearly defining core functions is a key step in assessing criticality – this establishes the 'goals' the Highways Agency is measuring criticality against. Core functions relate to the services the Highways Agency provides to its 'customers' rather than the activities it undertakes (e.g. safe roads and reliable journey times, rather than operating and maintaining the network).
- Whilst material-to-asset links are factual, there was some difficulty in establishing these. Some can be mapped from DMRB and standard specifications; however others, particularly technology assets, require supply input.
- Linking assets to core functions requires consideration of the properties an asset possesses which delivers elements of the core function. A single asset may provide multiple core functions; however, it may be a different asset property contributing to each.

- Testing of the framework has demonstrated the ability to quantify the relative criticality of materials providing the HA core functions and plot the criticality of individual materials using methods similar to those used in risk analysis.
- Material criticality issues are not routinely/ systematically considered by the Highways Agency or their delivery partners.
- There have been some isolated examples of supply disruption events, e.g. winter salt and steel.
- Where examples of criticality issues are cited, Highways Agency/ supplier response tends to have been reactive rather than proactive.
- In general, criticality risk is seen as low – with some concern cited over technology assets, bitumen and the impact that energy price may have. Currently there is a lot of uncertainty over the potential for future supply disruption and the impact it may have.
- There is a recognised shift towards the greater deployment of technology on the network. However, there is also uncertainty over whether this trend will continue as technology is anticipated to increasingly move ‘in-car’. There is also uncertainty over materials used to provide technology assets and whether future criticality issues may arise.
- It is difficult to decide what decisions should be taken when there is a landscape of uncertainty due to future change that could influence the materials usage significantly.

7 Appendices

Appendix A: ESD metric scores for material mapping – full table

Materials	ESD - Asset sensitivity (AS)	Assets	ESD - Function sensitivity (FS)	Functions
Coarse aggregates	1	Pavements	1	Providing access and connectivity
High specification aggregates	1			
Fine aggregates	0.5			
Bitumen	1			
Cement	0		0.5	Reliable journey times
Cement substitutes	0			
Concrete additives	0			
Copper	N/A			
Aluminium	N/A			
Ferrous metals	0		1	Safe roads
Other non-ferrous metals	N/A			
Fibre cable	N/A			
Plastics	N/A		N/A	Providing information to road users
Baked clay products	N/A			
Earth fill/ soil	N/A			
Paints and surface treatments	N/A			
Timber	N/A		N/A	Minimising environmental impact
Glass	N/A			
Road salt	1			
Unknown	N/A			
Coarse aggregates	1	Drainage	N/A	Providing access and connectivity
High specification aggregates	N/A			
Fine aggregates	1			
Bitumen	N/A		1	Reliable journey times
Cement	1			
Cement substitutes	0.5			
Concrete additives	0.5			
Copper	N/A			
Aluminium	N/A		1	Safe roads
Ferrous metals	0.5			
Other non-ferrous metals	N/A			
Fibre cable	N/A		N/A	Providing information to road users
Plastics	0.5			
Baked clay products	0.5			
Earth fill/ soil	0			
Paints and surface treatments	N/A		0.5	Minimising environmental impact
Timber	N/A			
Glass	0			
Road salt	N/A			
Unknown	N/A			

Materials	ESD - Asset sensitivity (AS)	Assets	ESD - Function sensitivity (FS)	Functions	
Coarse aggregates	1	Earthworks	0.5	Providing access and connectivity	
High specification aggregates	N/A				
Fine aggregates	0				
Bitumen	N/A		N/A	Reliable journey times	
Cement	0.5				
Cement substitutes	0.5				
Concrete additives	N/A		N/A	Safe roads	
Copper	N/A				
Aluminium	N/A				
Ferrous metals	N/A		N/A	Providing information to road users	
Other non-ferrous metals	N/A				
Fibre cable	N/A				
Plastics	N/A		0	Minimising environmental impact	
Baked clay products	N/A				
Earth fill/ soil	1				
Paints and surface treatments	N/A		Structures	1	Providing access and connectivity
Timber	0				
Glass	N/A				
Road salt	N/A	0.5		Reliable journey times	
Unknown	N/A				
Coarse aggregates	1				
High specification aggregates	N/A	N/A		Safe roads	
Fine aggregates	1				
Bitumen	N/A				
Cement	1	N/A		Providing information to road users	
Cement substitutes	0.5				
Cement substitutes	0.5				
Concrete additives	1	N/A		Minimising environmental impact	
Copper	N/A				
Aluminium	0				
Ferrous metals	1	N/A		Providing information to road users	
Other non-ferrous metals	0				
Fibre cable	N/A				
Plastics	0	N/A	Minimising environmental impact		
Baked clay products	0.5				
Earth fill/ soil	0				
Paints and surface treatments	1	N/A	Minimising environmental impact		
Timber	0				
Glass	0				
Road salt	N/A	N/A	Minimising environmental impact		
Unknown	0				
Unknown	0				

Materials	ESD - Asset sensitivity (AS)	Assets	ESD - Function sensitivity (FS)	Functions
Coarse aggregates	0.5	Restraint systems	N/A	Providing access and connectivity
High specification aggregates	N/A			
Fine aggregates	0.5			
Bitumen	N/A			
Cement	0.5		N/A	Reliable journey times
Cement substitutes	0.5			
Concrete additives	0.5			
Copper	N/A			
Aluminium	0.5		1	Safe roads
Ferrous metals	0.5			
Other non-ferrous metals	0			
Fibre cable	N/A			
Plastics	0		N/A	Providing information to road users
Baked clay products	N/A			
Earth fill/ soil	N/A			
Paints and surface treatments	0			
Timber	0		N/A	Minimising environmental impact
Glass	N/A			
Road salt	N/A			
Unknown	N/A			
Coarse aggregates	N/A	Markings and studs	N/A	Providing access and connectivity
High specification aggregates	N/A			
Fine aggregates	N/A			
Bitumen	N/A			
Cement	N/A		0.5	Reliable journey times
Cement substitutes	N/A			
Concrete additives	N/A			
Copper	N/A			
Aluminium	N/A		0	Safe roads
Ferrous metals	N/A			
Other non-ferrous metals	N/A			
Fibre cable	N/A			
Plastics	1		1	Providing information to road users
Baked clay products	N/A			
Earth fill/ soil	N/A			
Paints and surface treatments	1			
Timber	N/A		N/A	Minimising environmental impact
Glass	1			
Road salt	N/A			
Unknown	1			

Materials	ESD - Asset sensitivity (AS)	Assets	ESD - Function sensitivity (FS)	Functions
Coarse aggregates	0.5	Traffic signs	N/A	Providing access and connectivity
High specification aggregates	N/A			
Fine aggregates	0.5			
Bitumen	N/A		0.5	Reliable journey times
Cement	0.5			
Cement substitutes	0			
Concrete additives	0			
Copper	N/A			
Aluminium	1			
Ferrous metals	0.5		0	Safe roads
Other non-ferrous metals	0			
Fibre cable	N/A			
Plastics	1		1	Providing information to road users
Baked clay products	N/A			
Earth fill/ soil	N/A			
Paints and surface treatments	0		0	Minimising environmental impact
Timber	0			
Glass	N/A			
Road salt	N/A			
Unknown	1	Traffic signals	N/A	Providing access and connectivity
Coarse aggregates	N/A			
High specification aggregates	N/A			
Fine aggregates	N/A		1	Reliable journey times
Bitumen	N/A			
Cement	N/A			
Cement substitutes	N/A			
Concrete additives	N/A			
Copper	1			
Aluminium	0.5		0.5	Safe roads
Ferrous metals	0.5			
Other non-ferrous metals	1			
Fibre cable	1		1	Providing information to road users
Plastics	0.5			
Baked clay products	N/A			
Earth fill/ soil	N/A		N/A	Minimising environmental impact
Paints and surface treatments	0			
Timber	N/A			
Glass	0			
Road salt	N/A			
Unknown	1			

Materials	ESD - Asset sensitivity (AS)	Assets	ESD - Function sensitivity (FS)	Functions
Coarse aggregates	0.5	Lighting	N/A	Providing access and connectivity
High specification aggregates	N/A			
Fine aggregates	0.5			
Bitumen	N/A			
Cement	0.5		N/A	Reliable journey times
Cement substitutes	0.5			
Concrete additives	0			
Copper	1			
Aluminium	0.5		0.5	Safe roads
Ferrous metals	0.5			
Other non-ferrous metals	1			
Fibre cable	N/A			
Plastics	1		N/A	Providing information to road users
Baked clay products	N/A			
Earth fill/ soil	N/A			
Paints and surface treatments	0			
Timber	N/A		N/A	Minimising environmental impact
Glass	1			
Road salt	N/A			
Unknown	0.5			
Coarse aggregates	0.5	Soft estate	N/A	Providing access and connectivity
High specification aggregates	N/A			
Fine aggregates	N/A			
Bitumen	N/A			
Cement	N/A		N/A	Reliable journey times
Cement substitutes	N/A			
Concrete additives	N/A			
Copper	N/A			
Aluminium	N/A		N/A	Safe roads
Ferrous metals	N/A			
Other non-ferrous metals	N/A			
Fibre cable	N/A			
Plastics	N/A		N/A	Providing information to road users
Baked clay products	N/A			
Earth fill/ soil	1			
Paints and surface treatments	N/A			
Timber	N/A		0.5	Minimising environmental impact
Glass	N/A			
Road salt	N/A			
Unknown	0.5			

Materials	ESD - Asset sensitivity (AS)	Assets	ESD - Function sensitivity (FS)	Functions
Coarse aggregates	0.5	Fencing	N/A	Providing access and connectivity
High specification aggregates	N/A			
Fine aggregates	0.5			
Bitumen	N/A			
Cement	0.5		N/A	Reliable journey times
Cement substitutes	0			
Concrete additives	0			
Copper	N/A			
Aluminium	0.5		0.5	Safe roads
Ferrous metals	0.5			
Other non-ferrous metals	N/A			
Fibre cable	N/A			
Plastics	0.5		N/A	Providing information to road users
Baked clay products	0			
Earth fill/ soil	0			
Paints and surface treatments	0.5		0.5	Minimising environmental impact
Timber	0.5			
Glass	N/A			
Road salt	N/A			
Unknown	N/A			

Appendix B: Full list of survey questions

1. What is your influence over the types and quantities of materials used in HA infrastructure? Please describe how you have influence on the material requirements (e.g. specifying designs, using materials on site, supplying contractors, determining procurement policies etc.).
2. Please rate the importance of the following criteria when you make a decision on which materials to specify/use/supply. If you work in procurement, how important do you think these criteria are?
 - Fulfils the required function for the design
 - Meets HA specifications
 - Security of supply (e.g. are there supply risk issues?)
 - Purchase cost
 - Whole-life cost
 - Recycled content
 - Recyclability (e.g. it can be easily recycled at the end of its life)
 - Greenhouse gas emissions

Response options:

- I don't know/ N/A
- Never considered
- Rarely considered
- Sometimes considered
- Often considered
- Always considered

If you have any additional comments on the importance of these criteria in material decision making, please include these below.

3. Does your organisation (or division of the HA) have processes in place to identify future supply risk of raw materials?
 - Yes
 - No
 - Don't know

If yes please give details, including how far into the future

4. How do you (and your organisation) ensure that you have access to sufficient raw materials to deliver your operations, now and in the future?
5. Which raw materials do you rely on most for your operations? (i.e. If you are a desk-based designer, which materials do your designs rely on

most? If you work in procurement, which materials do you see as most important to HA operations?)

6. Are you able to substitute the materials you use in the event they become unavailable?

- Yes
- No
- Don't know

If yes please give details of substitution options for these materials (if any)

7. Are you aware of any HA functions or assets that rely heavily on a single material that is not easy to substitute?

- Yes
- No

If yes, please give details

8. Have your operations ever been affected by a material supply disruption?

- Yes
- Not that I'm aware

If so, what was/ were the material(s)?

9. For the material(s) listed in Question 14 why was supply disrupted?

10. For the material(s) listed in Question 14 what were the impacts of the supply chain disruption?

11. For the material(s) listed in Question 14 how was the problem solved and what were the lessons?

12. In your experience, how is infrastructure changing with respect to: (a) the functions provided by the HA; (b) materials; and (c) technologies?

13. How well understood are the supply chains for new materials and technologies that are being introduced into highways infrastructure?

- Poor
- Basic
- Good
- Excellent
- Don't know

Please give details if possible

14. Do you foresee any future issues for supply of materials and/or technologies in highways infrastructure, if so please give details

15. Do you have any other comments you feel are relevant to this project?

Appendix C: Literature Review



Infrastructure and material criticality: a literature review for the Highways Agency

Document: 1 Version: 1.2

Investigating Material Criticality

Highways Agency

January 2013



Infrastructure and material criticality: a literature review for the Highways Agency

Investigating Material Criticality

Highways Agency

January 2013

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Infrastructure and material criticality: a literature review for the Highways Agency

Investigating Material Criticality

Highways Agency

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Executive summary

Halcrow, working in partnership with the University of Leeds and TRL, has been commissioned by the Highways Agency to provide an initial assessment of material criticality. The project will identify the risks and opportunities material criticality currently presents and also potential material criticality issues associated with the continued delivery of Highways Agency services to the required standards into the future, maximising the level of return from their assets.

The stated objectives are:

- To understand the criticality risks associated with materials used in the maintenance, improvement and operation of the strategic road network.
- To provide the basis for ensuring future security of supply of essential materials needed to operate the strategic road network to the expected standards.
- To understand where potential resource vulnerabilities may exist.
- To explore opportunities from increased diversity of supply and substitutability.

Modern society is underpinned by the services provided by infrastructure and the components and technologies embedded within it. The maintenance and construction of infrastructure requires large quantities of materials to ensure the provision of these vital societal services.

The global material requirement for infrastructure is expected to double by 2050 if current trends continue, further increasing competition for resources. The HA consumes around 5.6Mt of materials annually across its contracts, the bulk of which are quarried aggregate materials. Other important materials include copper cabling and structural steel.

There are a number of incremental and radical innovations in the technology that underpins our highways infrastructure that are set to alter the flow and use of and demand for a wide range of materials. For example, the greater use and reliance on technology to inform, plan and manage journeys and traffic flows. Emerging technologies that are likely to be incorporated into the next generation of highways have the potential to both alleviate and intensify some material criticality related issues. As infrastructure evolves new materials may be introduced that are associated with novel technologies, and traditional materials may become scarce or obsolete.

A material is defined as critical to a particular function or economy if it has relatively high potential for supply disruption and the function or economy in question is vulnerable. This project is concerned with the potential threat posed to the continued maintenance, operation and evolution of UK highways infrastructure by supply disruption of vital materials.

There is a growing awareness of risks associated with resource insecurity but to date there has been no robust way of taking this risk into account in decisions, particularly for infrastructure. There are several resource security initiatives (including Defra's Resource Security Action Plan: making the most of valuable materials and work by the Technology Strategy Board) which aim to help UK businesses prepare for risks and opportunities posed by material criticality.

Several studies at a global, European and UK scale have used varying methodologies to identify materials whose supply characteristics pose most risk to economies. Most materials identified as critical are imported to the UK but indigenous aggregate is also identified. In particular, high specification aggregate for road surfacing is subject to medium-term supply risk concerns.

Academic research is underway to determine ways of measuring criticality in different contexts. The most advanced method to date has been developed by Graedel, et al. (2011). However, this approach is not appropriate for assessing the criticality of materials to infrastructure services. The Undermining Infrastructure project at the University of Leeds is addressing this gap with a methodology for criticality determination relevant for infrastructure services. This work will inform the approach to criticality assessment used in this project for the Highways Agency.

In developing a framework to assess criticality existing approaches to risk management and mitigating risks in both asset management and supply chain management should be considered. Consideration of risks should be integrated with organisational or business decision making processes and outcomes focused to optimise performance against serviceability indicators to achieve the lowest cost of ownership over the asset lifecycle. Material criticality issues should be considered in a holistic approach alongside other risks and performance criteria.

Material criticality should be a key consideration in the development of new highway technologies. This will give scope for material substitution and alternative approaches to be considered. Currently there is insufficient data available and no adequate process or framework devised to allow the accurate prediction of material criticality based on future innovations and technologies within the highways network (internationally or in the UK).

1 Introduction

Modern society is underpinned by the services provided by infrastructure and the components and technologies embedded within it. The generation, transmission and distribution of electricity, telecommunications, computing and data storage, mobility and international trade; all rely on physical infrastructure which is often interconnected globally, regionally and locally. Infrastructure must constantly respond to technological development, societal change, changes to trade and development, environmental change as well as fulfilling political and policy points of focus. To enable the functioning of an efficient and sustainable economy, infrastructure itself must be adaptable to change and resilient to potential threats and hazards.

Maintenance and construction of infrastructure requires materials. As infrastructure evolves (e.g. in response to the low-carbon agenda or changes in the services provided), the mix of materials contained therein changes. New materials may be introduced that are associated with novel technologies, and traditional materials may become scarce or obsolete on the Highways Agency network but freed up for other uses.

This project is concerned with the potential threat posed to the continued maintenance, operation and evolution of UK highways infrastructure by supply disruption of vital materials; referred to as *material criticality*.

Halcrow, working in partnership with the University of Leeds and TRL, has been commissioned by the Highways Agency to provide an initial assessment of material criticality. The work will identify the potential risks and opportunities material criticality presents to the continued delivery of Highways Agency services to the required standards into the future and maximising the level of return from their assets.

This report summarises existing relevant research and literature in the area to provide the foundation for the next stages of the project.

The literature review covers the following topics:

1. **Infrastructure services and material consumption:** an introduction to the material requirements of infrastructure, supply risk concerns and details of the UK infrastructure investment pipeline.
2. **Existing material criticality and resource security studies:** a summary of methods and results of studies to date relevant to the UK on criticality and resource security.
3. **Academic approaches to material criticality assessment:** this section covers the assessment framework developed by Graedel, et al. (2011) and introduces infrastructure-specific work which is currently underway at the University of Leeds.
4. **Resource security and resource efficiency:** policy developments and responses: a summary of policy responses to criticality and European and UK resource efficiency policy.

5. **Existing approaches to risk-based asset management and managing supply chain risk:** a summary of existing approaches to incorporating risk into asset management and supply chain management, and management and mitigation approaches which may be relevant to material criticality.
6. **Future highways infrastructure:** a discussion of what the future may look like for highway infrastructure and how this might impact on material demand on the trunk road network.

Where applicable, each section concludes by summarising relevant Highways Agency work or data which relates to the topic which will help inform the subsequent stages of the project.

A long-list of materials at risk of supply disruption is developed from existing studies (Table 1).

A series of separate working papers are being developed which will act as live reference documents throughout the project. These will be on the topics of:

- key HA functions, assets and material use;
- the approach to assessing criticality; and,
- stakeholder engagement and consultation.

2 Infrastructure services and material consumption

The provision of infrastructure services such as transport and mobility relies on physical infrastructure comprised of technologies (e.g. gantry signage), components (e.g. LED lights) and materials (e.g. indium). Existing infrastructure requires inputs of materials for maintenance, even without any growth in the scale of overall infrastructure. For example, a surface course of a road will be replaced before the road structure reaches the end of its life. Of course, increasing the scale of overall infrastructure, by for example, constructing additional roads requires additional material input. Material is stored in infrastructure during its useful life – termed ‘stocks in use’ – the quantity of which is determined by the level of input and output flows over time and the material composition of technology components. Quantities of the principal materials consumed by the Highways Agency are outlined in Section 2.3.

2.1 UK infrastructure investment

In the UK, significant investment is planned to rejuvenate ageing infrastructure and to facilitate the transition to a low-carbon economy (HM Government, 2011). The UK government’s National Infrastructure Plan (NIP) (2011) sets out investment in the following priority areas:

- **Transport:**
 - The road network – in order to reduce congestion and improve safety
 - Public transport – including the electrification of the Transpennine railway, technology to support smart ticketing and support for low-carbon buses.
 - Airports – Gatwick and Heathrow capital programme.
 - Ports – to support measures to reduce bottlenecks at freight terminals.
- **Energy:** investment aims to ensure security of supply and reduce the carbon intensity of electricity generation. Priorities include supporting new nuclear power stations, carbon capture and storage, wind energy and transmission and distribution networks.
- **Communications:** investment in roll-out of 4G mobile internet, improvements to rural mobile coverage and broadband.
- **Water, wastewater and flood risk management:** significant investment in the Thames Tideway Tunnel and national flood risk management programme.

The government also publishes an annual Infrastructure Pipeline (IP) which covers over 550 projects worth £330bn, most of which are programmed to start in the next four years (HM Treasury, 2012). This includes more than

£16bn of capital investment in highways works on Highways Agency, local authority and privately financed projects.

2.2 The material composition and intensity of infrastructure

Physical infrastructure is comprised of technologies and components which are in turn comprised of materials. In civil infrastructure, a highway is comprised of the pavement of which the asphalt surface course is a component. Bitumen and aggregates are its principal constituent materials. By unpacking infrastructure into technologies, components and materials, we can link infrastructure services (e.g. energy provision, mobility) to the materials that make the services possible (see Purnell, et al., 2012).

Overall demand for materials used in infrastructure globally has quadrupled since 1960 (Allwood, et al., 2011). Furthermore, the International Energy Agency (IEA) estimates that global raw material demand will more than double from current levels by 2050 if population and income trends continue (International Energy Agency, 2008). The UK economy consumes approximately 683 million tonnes of materials annually of which 451 million tonnes are non-fossil fuel materials such as minerals and biomass (Brown, et al., 2011). Of all material consumed in UK, 43% are imported. Around 160 million tonnes of aggregate materials are consumed in England each year to meet demand from construction and maintenance of buildings and infrastructure.

Much of the infrastructure in the NIP and IP will require conventional bulk construction materials such as steel and aggregate; materials which have formed part of infrastructure for hundreds of years. However, many of the technologies being introduced use materials that have not previously been required in large quantities for infrastructure. For example, rare earth magnets are required for the latest off-shore wind turbines and electric vehicles rely on batteries containing lithium.

If decisions about current and future infrastructure are taken without considering the supply chain characteristics of the materials that will be required, infrastructure services may become prohibitively expensive or impossible to maintain in the event of supply disruption. In order to avoid supply disruption (and the associated impacts to services), it is important that infrastructure planners are able to consider the supply chain characteristics of materials. Emerging approaches to criticality assessment aim to provide the framework to enable the consideration of risks to material supply and the vulnerability of infrastructure to supply disruption.

2.3 Highways Agency material use

According to data collected for the purposes of reporting greenhouse gas emissions, the HA purchases approximately 5.6Mt of materials each year (based on data from 2009-2012). Of this, 1.9 Mt (34%) is virgin aggregate material, 1.2Mt (21%) is ready-made asphalt mixture and 1.1Mt (20%) is recycled aggregate material. Other materials purchased include approximately 155kt of cabling (a large proportion of which is likely to be

copper), 261kt of salt and 24kt of steel (Highways Agency, 2012b). The nature of highways infrastructure means that quarry sourced materials dominate consumption across the three types of contract: major projects (MPs), managing agent contracts (MACs) and design, build, finance and operate (DBFO).

Summary:

- Infrastructure requires the input of large quantities of materials to ensure the provision of vital societal services. The global material requirement for infrastructure is expected to double by 2050 if current trends continue, further increasing competition for resources.
- The HA consumes around 5.6Mt of materials annually across its contracts, the bulk of which are quarried aggregate materials. Other important materials include copper cabling and structural steel.
- In theory both small (niche) and large volumes of materials used in Highways may be susceptible to material criticality.

3 Material criticality and resource security – existing studies

3.1 Resource (in)security and the concept of material criticality

There is a growing awareness that resource insecurity poses a threat to the systems on which we rely, driven by policy decisions and the scale and rate of growth in emerging economies. Chatham House has recently published a study of resource security across all raw materials concluding that “*volatility is the new normal*” and that “*the outlook is one of supply disruptions, volatile prices, accelerated environmental degradation and rising political tensions over resource access*” (Lee, et al., 2012). Despite the warning signals, recent research by the Carbon Trust suggests that most businesses are ill-prepared for the possibility of resource constraint with most business leaders reporting that they do not anticipate having to change their operations until 2018 at the earliest (Carbon Trust, 2012). This situation suggests the need to better understand, communicate and plan for the risks posed by resource scarcity. For raw materials, the concept of criticality attempts to address this need.

The typical expected lifetimes of physical infrastructure assets are anywhere from 15 to more than 100 years. So, in making infrastructure decisions now, we are assuming both an ongoing requirement for their services and that there will be sufficient availability of resources and materials to maintain assets over their lifetime. However, to date there has been no robust way of assessing whether decisions taken now will leave a technology or infrastructure system vulnerable to future material supply disruption. By making decisions without consideration of future material supply bottlenecks, the sustainability and resilience of infrastructure and the services it provides could be undermined (Purnell, et al., 2012).

This set of circumstances is not unique to risks posed by imported ‘spice metals’. There is also concern about the supply of conventional construction materials such as indigenously-won crushed rock aggregate, particularly for high performance applications (e.g. highway surfacing) (Lusty, et al., 2011; Thompson, et al., 2004). Significant additional infrastructure roll-out on top of baseline maintenance demand may increase the potential for supply disruption of traditional bulk materials, particularly at a regional scale.

There have been several attempts to identify critical materials at different scales, using different methods. Generally, most studies use a measure of the potential for supply disruption and a measure of economic importance (i.e. the vulnerability of an economy to supply disruption) to determine the relative criticality of materials to a national or regional economy.

Supply chain risks arise from physical disruption (e.g. conflict or natural disasters), market imbalances (e.g. high concentration of supply or monopoly) or government intervention (e.g. export restrictions). Any of these may cause an actual disruption (i.e. material unavailability) or a steep price increase. End users and functions – whether at a national, regional or

infrastructure scale – have varying levels of vulnerability to supply disruption (Erdmann & Graedel, 2011). For example, an unanticipated shortage of materials could cause production delays and lost revenue for some customers but others may be able to quickly substitute the material, component or technology with another to perform the same function. A material is defined as critical to a particular function or economy if it has relatively high potential for supply disruption and the function or economy in question is vulnerable. For an infrastructure provider who must ensure uninterrupted services, avoiding supply bottlenecks of important materials is crucial. The study of material criticality has emerged as a response to the understanding that for some functions (e.g. defence, infrastructure and low-carbon technologies), the direct and indirect implications of supply disruption can be serious and that there is a need for a new indicator to support decision-making].

It is important to note, however, that there is no universally accepted definition of (or method for determining) material criticality and that the topic remains the subject of on-going research by industry, government and academics. The next section reviews the major published criticality and resource security studies relevant to the UK (including those with a European and global focus) which have sought to identify critical or key materials. It summarises their scope, methods, results and recommendations.

3.2 Identifying criticality materials: existing studies and policy developments

The growing importance of imported materials for high-tech and low-carbon applications, as well as increasing concern about security of supply on the part of import-reliant nations, has resulted in a number of studies into criticality of materials upon which these technologies rely at different scales over the past few years. These studies have also identified some conventional construction materials (e.g. aggregates and copper) that may become critical due to their economic importance and lack of substitutes. Table 1 at the end of this section summarises the scope and findings of these studies.

This section also summarises policy responses from Defra, BIS and the Materials Security Special Interest Group.

3.2.1 European and global scale

The most influential study to date was undertaken by the European Commission and published in 2010 titled Critical Raw Materials for the EU (European Commission, 2010). This report was the first to investigate the criticality of non-fuel materials across the EU. It first develops a long-list of important materials and then applies an assessment method to determine their relative 'supply risk' and 'economic importance'. The supply risk measure uses four individual indicators which are then aggregated to give a single score for each material:

- The **Hirfindahl-Hirschman Index (HHI)** measure the concentration of supply. A high HHI indicates a high level of supply concentration from few countries (e.g. China currently supplies 97% of global rare earths and thus can use supply restriction as a powerful political tool) whereas a low score indicates that a large number of countries share similar levels of supply (and thus sufficient competition ensures that natural market operations limit the impact of restrictions by single suppliers).
- The World Bank's Worldwide Governance Indicator accounts for the **political and economic stability** of producing countries; the logic being that the higher the instability, the more at risk material supply may be.
- The **potential for material substitution** is also included (i.e. the degree to which the function of one material can be adequately performed by another) in this case determined by the expert opinion of Fraunhofer ISI, the EC's consultants for the report.
- The final indicator is a measure of the **recycling rate** of each material. The study uses the 'recycled content rate' in order to account for the level of availability to market of secondary materials. Recyclability (both technical and economic) helps to mitigate the effect of primary supply disruption by allowing extraction from obsolete stocks.

The measure of economic importance breaks down the main uses for each material and attributes the value added of the economic sector for which it is an input to each material. In this way, the criticality of materials to a particular function (e.g. wind turbines) is not specifically assessed, only the importance of the material to the wider EU economy. The report narrows down the initial long-list of materials based on their supply risk and economic importance scores. A third dimension of 'environmental country risk' (ECR) is then introduced to identify possible additions to the final list. In this methodology, either a high supply risk or a high ECR is sufficient to define a material as critical, provided it is also of high economic importance. The ECR uses Yale University's Environmental Performance Index in order to identify instances where a country is more or less likely to introduce stringent environmental legislation that may restrict the mining and production of a material.

The study uses a time horizon of 10 years where data availability allows, but it is essentially a static snapshot of criticality at a point in time. The final list of 14 materials identified as critical to the EU is included in Table 1 along with key recommendations. It is important to note that the report highlights aggregates (crushed rock, sand and gravel) as potentially critical at a regional and national scale in the EU but that its methodology and focus on imported materials does not allow for their assessment.

At a global scale, the United States Department of Energy has undertaken work to determine the risks posed to low-carbon energy systems by material supply disruption (U.S. Department of Energy, 2010). This work uses a

similar method to the EC study employing measures of 'supply risk' and 'importance to clean energy' to assess the criticality of a range of materials. These are then plotted on a matrix to compare relative criticality. The supply risk metric consists of five categories: basic availability, competing demand, political and social factors, co-dependence and producer diversity. The importance metric is comprised of measures of demand from clean energy technologies and substitutability limitations. Each contributory factor is qualitatively scored and weighted. The analysis was completed for two timescales: short term (0-5 years) and medium term (5-15 years). Materials identified as critical in both timescales, along with recommendations for mitigation, are displayed in Table 1.

The British Geological Survey has developed its own Risk List index of materials subject to supply risk at a global level (British Geological Survey, 2012). This is a basic assessment of supply risk using four measures – scarcity (crustal abundance), production concentration, reserve base distribution and governance – which are given values of 1-5 and aggregated. It is important to note that this is a supply risk index only and it does not attempt to measure the vulnerability of functions or the importance of materials to the economy. The study does not look at future trends and so represents a snapshot for 2012. The materials considered most at risk are again included in Table 1.

3.2.2 UK scale

Defra's review of material criticality (Defra, 2010) was compiled as part of its Sustainable Consumption and Production Evidence Programme. It was intended as a scoping study to identify biotic and abiotic non-fuel resources that may pose a risk to different economic sectors in the UK and to act as an evidence base for resource efficiency policies. Unlike the EU study, it does not set out to develop a definitive list of critical materials but instead uses a basic literature-review approach to their prioritisation.

The methodology first identifies a long-list of resources which are important to UK businesses. It then prioritises these for each economic sector of which construction and engineering are the two most relevant in this case. The report uses a number of criteria to prioritise resources including supply domination, geopolitical influence and press coverage.

For each criterion, a score is given based either on available data or on a subjective assessment. A stakeholder consultation was also undertaken with for each sector. The list of 12 key resources identified by Defra's review is included in Table 1 along with the main recommendations from the report.

Table 1: summary of existing criticality and resource risk assessment studies

Title, author and date	Critical materials for the EU, European Commission, 2010	Critical materials Strategy, US Department of Energy, 2010	Risk List, British Geological Survey, 2012	Review of the Future Resource Risks Faced by UK Business and an Assessment of Future Viability, AEA Technology for Defra, 2010 Raw materials critical to the Scottish economy, AEA Technology for SNIFFER,
Purpose and scope	<ul style="list-style-type: none"> - Identify and assess criticality of imported materials to EU economy - Scope is EU economy 	<ul style="list-style-type: none"> - Identify materials critical to energy technologies and mitigate - Scope is clean technologies globally 	<ul style="list-style-type: none"> - High level assessment of supply risk for 41 elements - All indicators used are at a global level, only covers supply risk and not vulnerability or importance 	<ul style="list-style-type: none"> - Reviews resource risks to UK/Scottish businesses
Method summary	Assessments of supply risk and economic importance	Uses measures of supply risk and importance to clean technology	Several indicators are combined to into a risk score for each material	Literature review and prioritisation by economic sector
Time horizon	Static study, recommendation to update every 5 years	Short (0-5 years) and medium (5-15 years) term assessments	Static study, updated every year	These studies are static based on data relevant in 2010
Materials identified (long list of materials)	Antimony, Beryllium, Cobalt, Fluorspar, Gallium, Germanium, Graphite, Indium, Magnesium, Niobium, Platinum Group Metals (6 elements), Rare Earth Metals (17 elements), Tantalum, Tungsten	<ul style="list-style-type: none"> - Critical short term: Dysprosium, Europium, Indium, Neodymium, Terbium, Yttrium - Critical Long-term: Neodymium, Dysprosium, Terbium, Europium, Yttrium 	41 elements are assessed. Top 10 most at risk: Rare earths, Tungsten, Antimony, Bismuth, Molybdenum, Strontium, Mercury, Barium, Carbon (Graphite), Beryllium	Both studies: Aggregates, Cobalt, Copper, Fish, Indium, Lead, Lithium, Palm Oil, Phosphorus, Rare Earth Elements, Timber, Tin
Key recommendations	A large range of policy recommendations on data collection, access to primary materials and critical material recycling	Sets out US national R&D initiatives and measures for international cooperation on critical materials	No specific recommendations are given	Recommends that businesses gain a better understanding of resource dependencies and for government to think more strategically about resources

For the construction sector, aggregates, timber and copper were considered at particular risk whilst for the engineering sector, the supply of rare earths, copper and indium were considered to pose the most risk. Importantly for highways infrastructure, aggregate resources are identified as at risk of supply disruption due to increasing transport costs and planning restrictions on new permissions. A similar report was undertaken by the Scotland and Northern Ireland Forum for Environmental Research (SNIFFER) for Scotland based on the information collected for the Defra study (and it therefore identifies the same 12 key resources) (SNIFFER, 2011).

As well as summarising existing resource scarcity studies, Table 1 also highlights the long-list of materials that can be seen as posing varying levels of risk to UK businesses and infrastructure (see materials row). Due to the fact that all studies use different methodologies and scopes, it is not possible at this stage to definitively rank materials according to their levels of supply risk. Rather, the lists can be seen as the best available assessment by a range of national and international government bodies. Despite the methodological differences, rare earth elements are identified in all studies which reflects the view that they are currently subject to high supply risk.

3.2.3 Studies on aggregate materials

Whilst certain indigenous materials are identified as key resources in the Defra and SNIFFER studies, there has been little work to understand the criticality of these materials at the national and regional level or indeed sector or industry specific vulnerabilities. Of particular concern for highways is 'high specification aggregate', defined as having a polished stone value of 58 or higher which is typically used for surface course applications (Thompson, et al., 2004). Whilst the Managed Aggregate Supply System (MASS) is designed to ensure sufficient future supply of aggregate materials, there are constraints on obtaining new permissions (e.g. environmental protection) and land banks are held for crushed rock, potentially masking shortages of more valuable high specification materials. Aggregates are highly sensitive to rising transport costs which is of particular concern in areas reliant on imports by road. Work is on-going as part of the Undermining Infrastructure¹ project to assess the criticality of indigenously-sourced materials including aggregates at a sub-regional level (i.e. higher resolution than traditional regions). Figure 1 shows an initial draft map of the potential for supply disruption for crushed rock; the darker the area, the higher the potential for supply disruption. Further background to the issues contributing to aggregates supply risk can be found in an online project briefing note (see Revell, 2012).

¹ Undermining Infrastructure is an EPSRC-funded project at the University of Leeds which is defining methods of assessing the criticality of materials to infrastructure services.

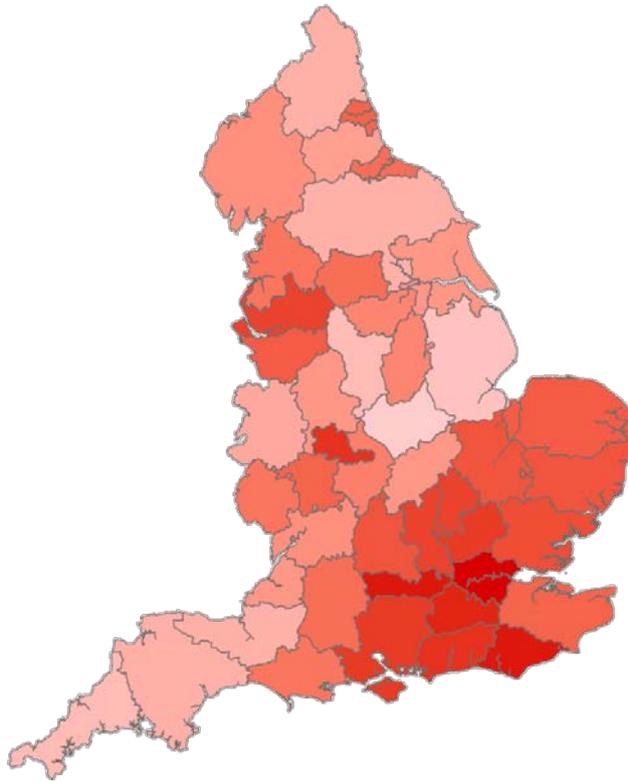


Figure 1: crushed rock potential for supply disruption, initial draft results

Given the potential for supply risk of primary materials, along with cost and sustainability considerations, aggregate materials are widely recycled at end of life. There are technologies enabling both in and ex-situ recycling of asphalt materials planed from the road surface during maintenance.

Indeed, the recycling rate for such materials is thought to be 100% with most reclaimed asphalt planings (RAP) currently re-used as un-bound material in lower pavement layers or as construction fill. However, it is estimated that no more than 10% of RAP arisings are currently recycled back into the new asphalt of roads (Barritt, 2012) meaning that there is almost always a down-cycling into lower-value applications. There are case studies demonstrating that high quality surface course can be designed containing up to 50% RAP although achieving this level of recycled materials requires additional performance testing (see Annex G of SNIFFER, 2011).

Increasing the recycling levels of high-PSV RAP into the surface course has the potential to reduce requirements for primary high specification roadstone which is in high demand. A European-level project called Re-Road, funded under the FP7 framework, focussed on facilitating higher levels of closed-loop recycling of reclaimed asphalt (Re_Road, 2012). This was primarily achieved by enhancing the evidence base with regards to asphalt recycling to bound courses, by understanding the physical and chemical attributes of RAP, both as a separate entity and as part of a new road surface, by understanding the technological enhancements needed to incorporate higher levels of RAP into asphalt mixtures, and by understanding the environmental consequences of higher recycling levels.

Closed-loop recycling of asphalt returns RAP back to new asphalt applications. This process has distinct advantages over RAP recycling to unbound applications such as sub-base or fill, since the residual bitumen present in the RAP can displace some of the requirement for fresh bitumen in the new asphalt. The active properties of bitumen are preserved into the second and even further uses (Mollenhauer, et al., 2012). In criticality terms, closed-loop recycling offers benefits in terms of preserving two finite materials: aggregates and bitumen. Bitumen, as crude oil fraction with the most significant reserves in politically susceptible regions, may be classed as having resource 'insecurity' issues as well as criticality issues associated with its reserves.

The environmental benefits of the preservation of bitumen and aggregates were demonstrated in the life cycle assessment (LCA) that was undertaken as part of the Re-Road project. Figure 2 presents some of the key high level results that arose from the LCA, in which the results of recycling scenarios are presented relative to those of a virgin asphalt scenario. The graph presents five scenarios where an asphalt pavement has been built and is maintained over a 60 year service life, using asphalt containing a different level of RAP, in both initial construction and maintenance:

- All virgin material – no RAP is incorporated into any of the asphalt mixtures;
- 50% recycled sub-base – 50% unbound RAP replaces virgin aggregates in the sub-base layer;
- 15% recycling in one bound course – 15% RAP is incorporated into the surface course asphalt mixture;
- 30% recycling in one bound course – 30% RAP is incorporated into the surface course asphalt mixture;
- High recycling – 30% RAP is incorporated into the surface, binder and base course asphalt mixtures and 50% unbound RAP into the sub-base, this represents an 'aspirational but feasible' scenario.

In terms of material criticality, the impact category 'abiotic depletion' should be considered. This impact category concerns the level of depletion of finite, non- biological (and therefore non-regenerative), resources that the scenario consumes. The enhanced benefit of recycling to bound rather than unbound applications is clearly demonstrated. Aside from abiotic depletion, a range of six other impact categories are presented that relate to other aspects of environmental performance.

The ultimate aim of the Re-Road project was to enhance surface-to-surface course recycling. This practice not only preserves aggregates and bitumen but also the high PSV properties of the aggregates present in the pre-existing surface course, providing that the material is correctly handled and segregated from other sources of RAP. As discussed previously, high PSV

aggregate is a more critical resource than regular pavement grade aggregates.

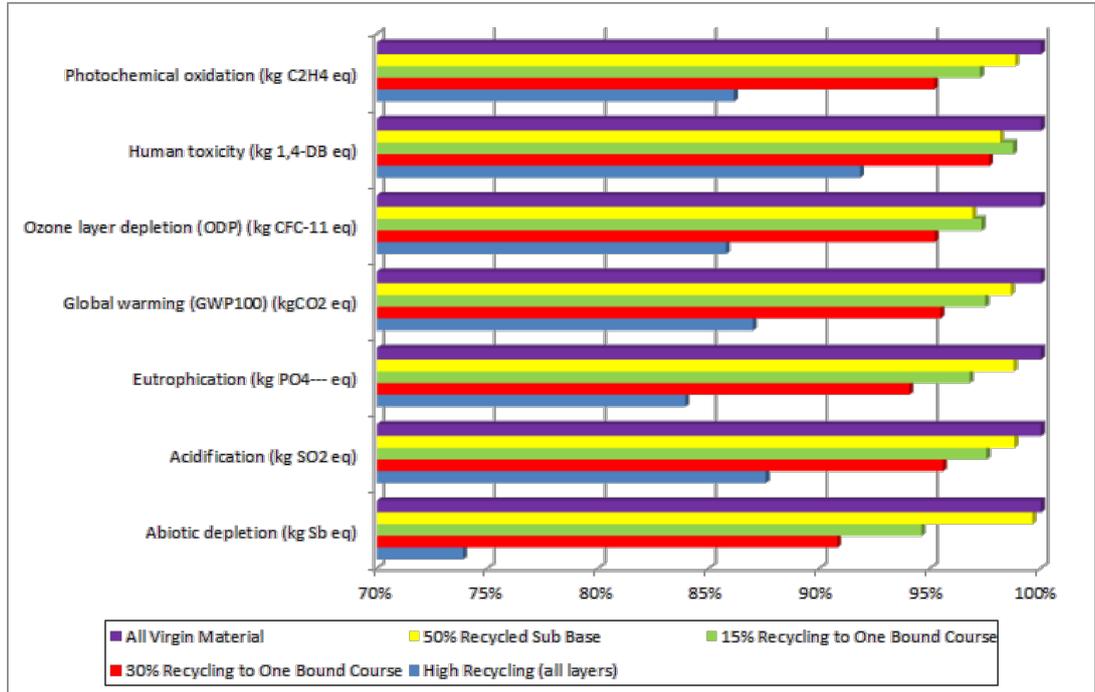


Figure 2: Comparing the relative benefits of alternative asphalt recycling scenarios²

Figure 3 indicates the added benefit of preserving high PSV aggregate in surface-to-surface course recycling (this effect was not considered in Figure 2). Here a supply scenario for South East England is considered, which requires high PSV aggregates to be imported from Northern Ireland by ship to a wharf on the coast. This is one active supply route for South East England, by rail freight from Wales to London is another that is commonly used.

The effect of preserving high PSV aggregates is observed across all of the impact categories. The additional benefit arises as a result of avoiding the additional transport associated with the more disparate sources, and the additional energy input required to process them, since they are typically a harder grade than regular aggregates.

The HA has undertaken work to explore how best to embed sustainability within pavement design, including the potential to adopt a cradle-to-cradle approach to maximise resource recovery. This is discussed in section 5.3.

² Reproduced from Wayman et al. (2012)

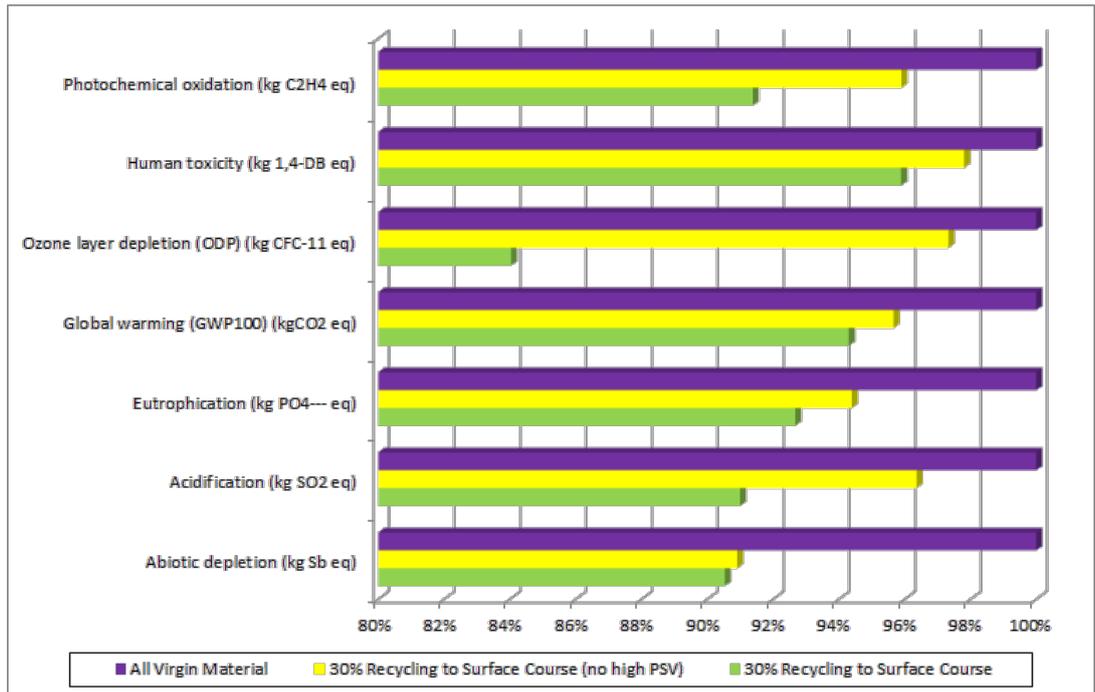


Figure 3: The additional environmental benefit of preserving high PSV aggregates in recycled asphalt

Summary:

- A material is defined as critical to a particular function or economy if it has relatively high potential for supply disruption and the function or economy in question is vulnerable.
- There is a growing awareness of risks associated with resource insecurity but to date there has been no robust way of taking this risk into account in decisions, particularly for infrastructure.
- Several studies at a global, European and UK scale have used varying methodologies to identify materials whose supply characteristics pose most risk to economies. The long-list of materials identified is included in Table 1.
- Most materials identified as critical are imported to the UK but indigenous aggregate is also identified. In particular, high specification aggregate for road surfacing is subject to medium-term supply risk concerns.
- Work is underway at the University of Leeds to develop a methodology for determining the criticality of indigenous materials at a sub-national level.
- Recycling is a vital pathway that is available to preserve critical materials. The practice of recycling often realises additional benefits in terms of reducing other environmental impacts as well as preserving finite resources.

4 Academic approaches to criticality assessment

In addition to interest from governments and businesses, criticality is also now the subject of significant academic research. Several research teams are working to develop methods of assessing criticality in different contexts. An approach to determining the criticality of metals has been developed by Thomas Graedel and his team at Yale University (Graedel, et al., 2011). This focuses on assessing the criticality of a metal at three alternative levels; corporate, national and global. This method includes indicator categories of supply risk, vulnerability to supply risk and environmental implications. The method is not dissimilar to that adopted in the EC study although a separate set of indicators is used for vulnerability at corporate, national and global levels. Importantly, the work presented by Graedel, et al., 2011 does not set out to identify critical materials but develops an assessment framework intended to be applied at each of the three levels. The approach gives a snapshot of criticality at a point in time although there is an attempt to include indicators of medium and long term supply risk. The framework for supply risk is displayed below in Figure 4.

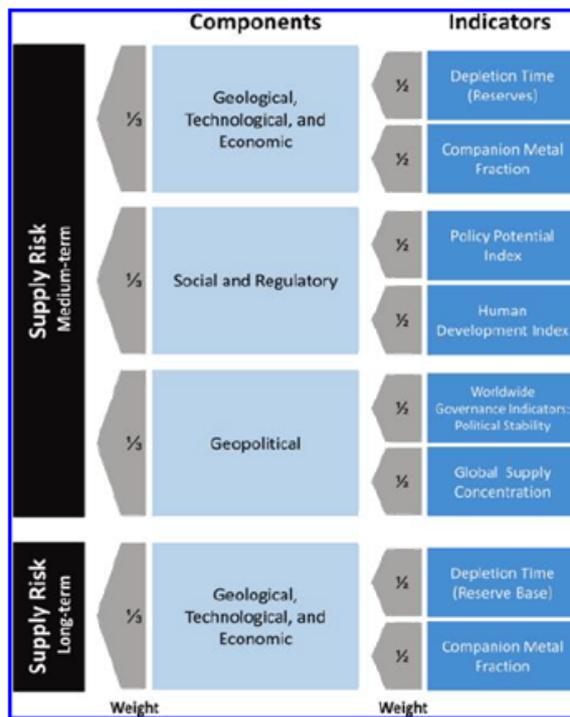


Figure 4: Indicators of supply risk developed in Graedel et al. (2011)

Research currently underway at the University of Leeds, as part of the EPSRC-funded Undermining Infrastructure (UI) project, seeks to specifically investigate the vulnerability of infrastructure services to material criticality. Whereas Graedel, et al., 2011 focuses on quantifying the criticality of a material in a business or geographical context, this work aims to assess the extent to which the combined potential for supply chain disruption of a group of materials could constrain a particular societal goal or service (e.g. low-carbon transition, road safety, mobility). The UI project requires an

assessment of the combined potential of materials that enable a key infrastructure service as opposed to analysis of one material only; its focus is on many materials in one application rather than looking at the many applications for one material. This means that the effects of any disruption are specifically concerned with the ability to deliver the infrastructure service, as opposed to the effect on a business's bottom line or national GDP.

The UI project is currently developing a methodology for criticality assessment. This includes two indicator categories: potential for supply chain disruption (PSCD) and exposure to supply disruption (ESCD). Like Graedel's work, each category consists of a range of metrics which are combined to arrive at scores for PSCD and ESCD. The UI method forecasts metrics in order to estimate future criticality, something that has not been attempted in previous work.

Summary:

- Academic research is underway to determine ways of measuring criticality in different contexts. The most advanced method to date has been developed by Graedel, et al., 2011. However, this approach is not appropriate for assessing the criticality of materials to infrastructure services.
- The Undermining Infrastructure project at the University of Leeds is addressing this gap with a methodology for criticality determination relevant for infrastructure services. This work will inform the approach to criticality assessment used in this project for the Highways Agency.

5 Resource security and resource efficiency: policy developments and responses

5.1 Resource security: policy responses

Emerging concern about criticality and resource insecurity on the part of government and the private sector has resulted in several policy documents and strategies. A Resource Security Action Plan was published in 2012 by Defra and the Department of Business Innovation and Skills. This document provides a framework for action in the short term to address resource risks and for building partnerships between Government and businesses. Key actions include:

- Funding for an Innovation Challenge Fund for closed loop recycling by small businesses;
- Improving data capture on waste electronic and electrical equipment (WEEE);
- The launch of a critical resources dashboard to improve data provision for decision-making on resource risks, and
- Demonstration trials for the recovery of critical materials through the WEEE treatment process.

The Material Security Special Interest Group of the Technology Strategy Board Knowledge Transfer Partnership has recently released a consultation draft report titled Innovation Opportunities and Material Security. The report aims to present a summary of the potential impacts and opportunities for the manufacturing sector that may result from the supply disruption of the 14 materials identified in the EC study. It identifies six sectors and presents a SWOT analysis for each to highlight opportunities for innovation (Technology Strategy Board, 2012). For the transport sector, materials contained in batteries and electric motors are seen as posing potential risk whilst in the built environment sector, access to aggregate resources is again identified as a potential future issue.

5.2 Resource efficiency and recovery

5.2.1 European level policy

There has long been a focus on improving waste management and resource efficiency in order to realise cost savings and respond to sustainability drivers (see European Commission, 2008). Alongside substitution and strategic stockpiles (e.g. the MASS), many of the obvious responses to criticality risks also involve increasing material efficiency to reduce material requirements and to move towards the goal of circular economies. The EU commission sees resource efficiency as key to maintaining security of supply of key materials but also for wider regional security and economic imperatives.

In 2011, the EU commission launched a flagship initiative for a resource efficient Europe as part of its Europe 2020 Strategy (European Commission, 2011). This aims to provide a long-term framework for actions across member states to support policy agendas for climate change, energy, transport, industry, raw materials, agriculture, fisheries, biodiversity and regional development. It aims to increase certainty for investment and innovation and to ensure that national-level policies factor in resource efficiency. This was followed in 2012 by the EC Resource Efficiency Platform's (EREP) Manifesto for a Resource Efficient Europe (European Commission, 2012) which aims to accelerate Europe's transition to a circular economy. Key actions include:

- Creating a regulatory framework which encourages public and private investment in resource-efficient technologies, systems and skills;
- Abolishing environmentally damaging subsidies and shifting the tax burden away from jobs in resource efficiency;
- Setting targets on use of land, materials, water, greenhouse gas emissions, and biodiversity loss and indicators for monitoring progress.

The EREP will publish more detailed policy measures in summer 2013.

5.2.2 UK national policy and action

At the UK level, resource efficiency is addressed in the sustainable development strategy *Securing the Future* (HM Government, 2005). It is also present in various pieces of waste management strategy and to some extent in planning, transport and procurement strategies. *Securing the Future* includes a goal of achieving sustainably-built and managed properties and roads throughout the public sector (WRAP, 2012a). It also directed landfill tax receipts to help fund the Business Resource Efficiency and Waste Programme (BREW) which funded various resource efficiency programmes until it finished in 2007/08.

The Department for Transport's Sustainable Procurement Strategy noted the importance of considering natural resource use in procurement decisions. However, this strategy has since been superseded by a move to 'central category procurement' (Department for Transport, 2012).

Although not related to traditional highways materials, WRAP has undertaken work on critical resource recovery (mainly rare earths and platinum group metals) that may have transferrable lessons for other sectors. Research undertaken in 2011/12 aimed to determine current understanding of critical resource recovery globally and to assess current capacity for recovery in the UK from the WEEE waste stream. The study reports that there is a low level of awareness in industry as to the importance of critical materials and a low level of capacity for their recovery. It recommends the introduction of standards for critical material recovery as well as improved segregation and, importantly, that materials stay in the UK and are not shipped abroad for reprocessing (WRAP, 2012b). Although the

characteristics of construction waste streams are different from that of WEEE, there are undoubtedly parallels in terms of awareness of the importance of recovery techniques.

The ICE Demolition Waste Protocol was established in 2003 with the aim of optimising the demolition process to maximise the percentage of recoverable material (see ICE, 2012).

5.3 Highways Agency resource efficiency work

The HA's Sustainable Development Plan for 2012-2015 (Highways Agency, 2012a) includes measures to better understand supply chain resource use, to work with suppliers to encourage resource efficiency and to work with WRAP and industry stakeholders to develop a resource efficiency strategy. It also includes a commitment to set a target to reduce reliance on virgin aggregate materials.

The HA has recently commissioned research on 'embedding sustainability in pavement design, construction and maintenance'. The project involved several tasks to understand current approaches and attitudes to pavement recycling and to recommend a course of action for the HA. The project investigated the potential for cradle to cradle pavements and proposes an engagement questionnaire on pavement materials for use with contractors. A survey was also undertaken which concludes that there is a high level of uncertainty amongst supply chain stakeholders as to current pavement recycling practice.

Summary:

- There are several resource security initiatives (including the Defra Action Plan and the TSB work) which aim to help UK businesses prepare for risks and opportunities posed by material criticality.
- Resource efficiency is a key policy driver at the European level. This is not as well reflected in UK national policy although WRAP has undertaken significant work to embed resource efficiency in many UK sectors.
- Identifying opportunities to use critical resources more efficiently is one means of reducing the risk to infrastructure services.

6 Existing approaches to risk-based asset management and managing supply chain risk

As described in the previous sections, emerging approaches to assessing criticality are based around risk – specifically the likelihood that supply chain disruption may be experienced, and the consequence of any potential disruption on an organisation’s ability to maintain the required service level of their assets.

Risk is a well understood concept and direct risks are already managed effectively in many business sectors including asset management and supply chain management. Both ISO (2009) and the Institute of Risk Management (IRM) (2002) set out standards, principles and guidelines for risk management in terms of identification, assessment and treatment. Whilst direct risks tend to be well understood, indirect, or emerging risks are managed but are less well understood in terms of potential impacts and intervention strategies (Institute of Risk Management, 2004). In order to adequately control indirect risks cross industry sector collaboration may be required.

The following sections describe relevant approaches to risk management in both asset management and supply chain management.

6.1 Risk based approaches to asset management

Traditionally asset management investment decisions have been taken based on historical analysis of expenditure levels required to maintain a level of serviceability and estimate asset lives (Lumbers & Kirby, 2003). PAS 55 (Optimal management of physical assets), developed by the Institute of Asset Management (IAM) and adopted by the BSI, sets out the key principles of joined-up and optimised asset planning (Institute of Asset Management, 2008).

Integration is at the heart of good practice asset management defined in PAS 55. Assets are managed at a number of levels, as illustrated in Figure 5. There is a need for layered integration to address the underlying challenges of optimising the blend of costs, performance, risks and sustainability. Cascading from the organisational strategic goals, cost, performance and sustainability goals must be considered at asset portfolio, system and individual asset level. In order to effectively consider and manage criticality a similar approach may be required to ensure consideration of criticality is integrated into the various levels of asset management and planning.

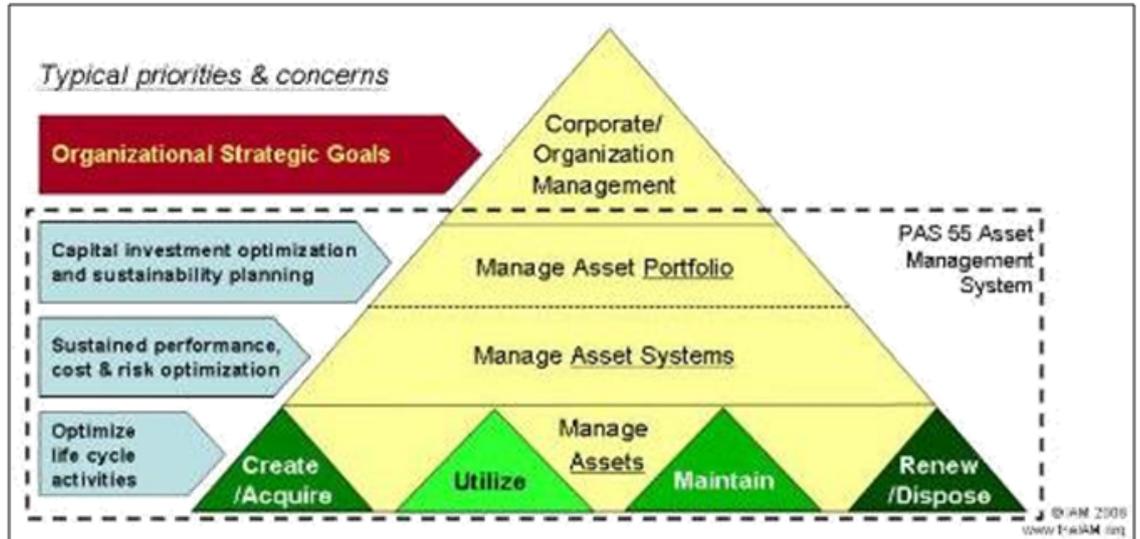


Figure 5: Levels of an Asset Management System (Institute of Asset Management, 2008)

PAS 55 defines a series of vital attributes used to distinguish good practices in joined-up asset management from historical approaches to ‘merely managing the assets’ (Figure 6). PAS 55 sets out the principles for achieving optimal asset management when considering multiple objectives.

A key component of PAS 55 is that integrated asset management should incorporate a risk based approach. This ‘forward looking’ risk based approach considers the future cost of maintenance to meet regulatory requirements, the cost of failure and the value placed on service improvements by customers (if appropriate).

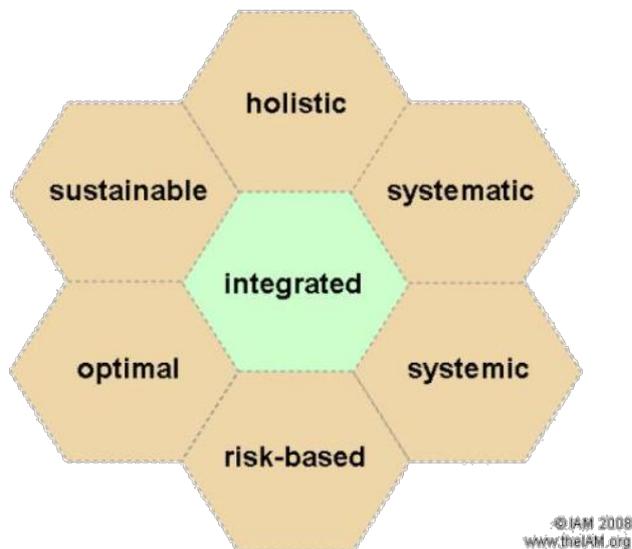


Figure 6: Key Principles of PAS 55 (Institute of Asset Management, 2008)

PAS 55 is an effective framework because it promotes a structured and holistic approach to asset management. Materials criticality can, and should, be one component of a holistic, cross-disciplinary framework. Asset

management tools should be assessed to see whether they can be adapted to include material criticality issues.

In the water industry UKWIR have developed the Common Framework for Capital Maintenance Planning. The Framework adopts a risk based approach justifying capital maintenance on the basis of current and forecast probability and consequences of asset failure with or without investment. The Framework provides a process to make the business case for the required level of future investment. Figure 7 shows the Common Framework process.

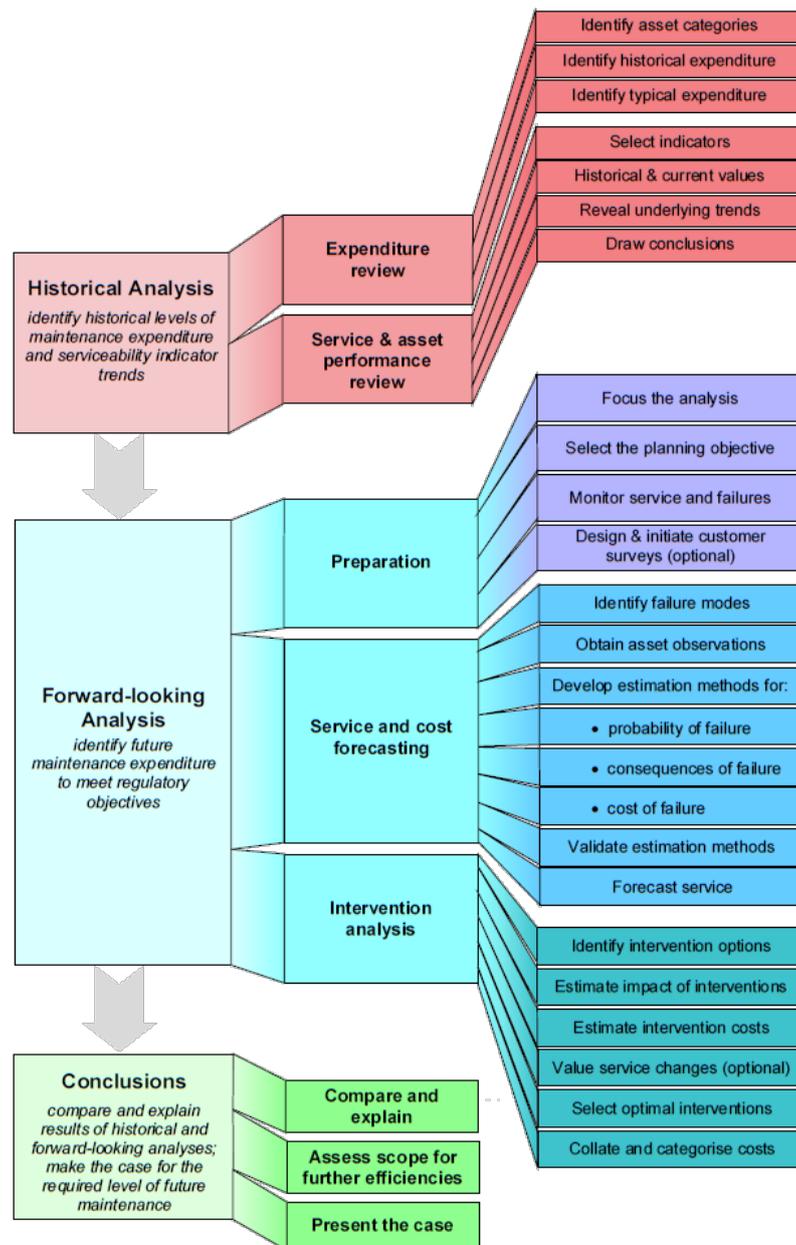


Figure 7: The Common Framework Process (UKWIR, 2002)

A key component of the Common Framework is the use of serviceability indicators which measure the service being provided to customers and the environment, and the performance of an asset in fulfilling its intended function. The Common Framework forecasts future service taking account of proposed capital maintenance and operational changes. Outcome focused asset management is common to both the Common Framework and best practice in resilience planning.

The Common Framework identifies failure modes, estimating the probability, consequence and cost of failure and forecasts future service levels. Interventions are subsequently analysed to compare their impact on service level, capital cost and cost of failure to select the optimal interventions.

In following a risk based approach to asset management, assets are assigned a failure rate which may degrade over time; a cost is associated with each failure, providing a total cost of failure for the asset. Capital maintenance interventions are analysed comparing their capital cost with the future cost of failure with and without the intervention.

The cost of failure may be built up from a variety of impacts, from the direct cost of repair, costs associated with loss of service, wider environmental or social costs, in this way interventions can be prioritised based on for example, the number of people affected by an asset failure. Considering the trade off between capital costs and operational costs, including failure costs, allows the total cost of ownership to be optimised over the life of the asset. In an integrated approach to asset management this cost of failure would also be considered alongside other cross-disciplinary objectives.

When considering system resilience it may be necessary to consider events outside those normally experienced – a system ‘shock’. A resilient system will continue to function after experiencing a ‘shock’ event even if its functionality has suffered some degradation (Rogers, et al., 2012). If a shock event changes the functionality of a system permanently the so called ‘tipping point’ is reached (Gladwell, 2000). At this point the system does not recover, it may still be considered to be resilient but is altered from the original system (Rogers, et al., 2012). Some supply chain disruption events may be shock events – the resilience of the assets affected will impact on the asset vulnerability to these events.

Criticality should be considered alongside other indicators in an integrated asset management approach. Through understanding the criticality of materials in asset planning, the consequences of decisions can be considered over the life of the asset. For example, if a new technology is being considered for application to a network of assets the current and future supply of materials as well as the substitutability of the materials to fulfil a function should be considered. Taking a holistic approach to risk management allows the real ‘cost’ of managing and maintaining an asset to be considered.

Whilst the Common Framework is presented as a linear approach it fits within a cyclical business planning process leading to continuous

improvement and iterative management of risks. Figure 8 presents a typical iterative approach to risk management, in this case for addressing climate change, however, the management, decision making and learning cycle, similar to that used by the UK Health and Safety Executive (HSE) is equally applicable to other risks.

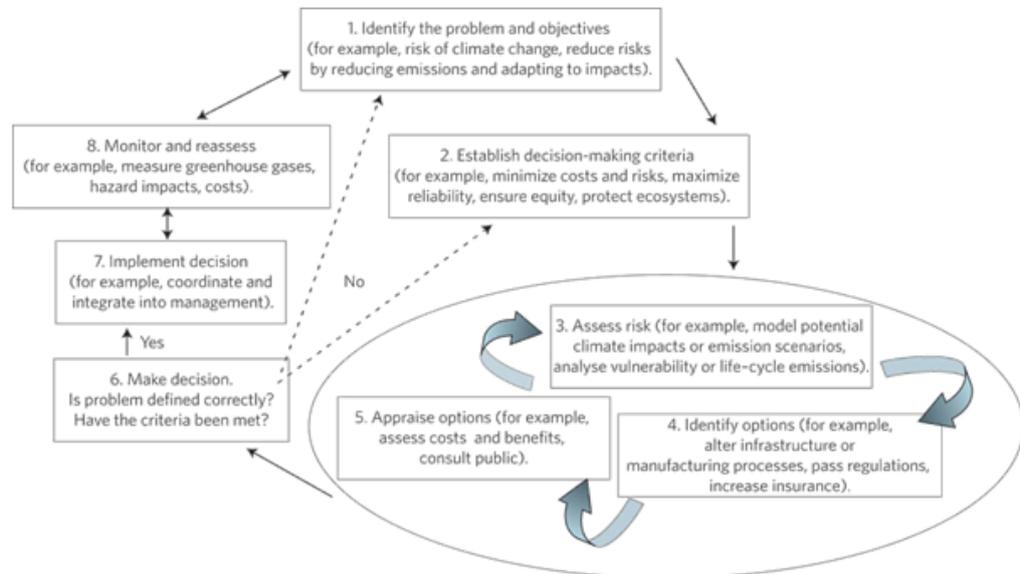


Figure 8: The steps in an 'iterative risk-management approach' for addressing climate change (Arnell, 2011)

Within a systematic asset management system this cycle can be used to assess multiple risks, including criticality. The criticality assessment process being investigated by this work would be applied at stage 3 with management and mitigation options being considered at stage 4.

6.2 Supply chain risk management

In recent years natural disasters as well as industrial incidents have exposed supply chain risks, particularly in the manufacturing sector and resulted in a surge in interest and publications (Craighead, et al., 2007). In some cases the drive for financial and process efficiencies has come at the expense of resilience and vulnerability to supply chain risk. For example, the move towards “just-in-time” elongated globalised supply chains and supplier rationalisation have all had the effect of making supply chains more vulnerable to disruption (IBM, 2008). Familiar cases such as the 2011 8.9 magnitude Japanese earth quake (Park, et al., 2012), a fire at a single sub-supplier factory severely affecting the mobile phone manufacturer Ericsson in 2000 (Norrman & Jansson, 2004) or supply shortages affecting both Boeing and Nike (IBM, 2008), have illustrated some of the various factors posing a risk to modern globalised supply chains.

The World Economic Forum (WEF) categorise triggers of supply chain disruption into four categories: environmental, geopolitical, economic and technological (World Economic Forum, 2012). Figure 9 summarises survey responses collected by the WEF, ranking supply chain disruptions as most

likely to provoke significant and systemic effects on supply chain or transport networks.

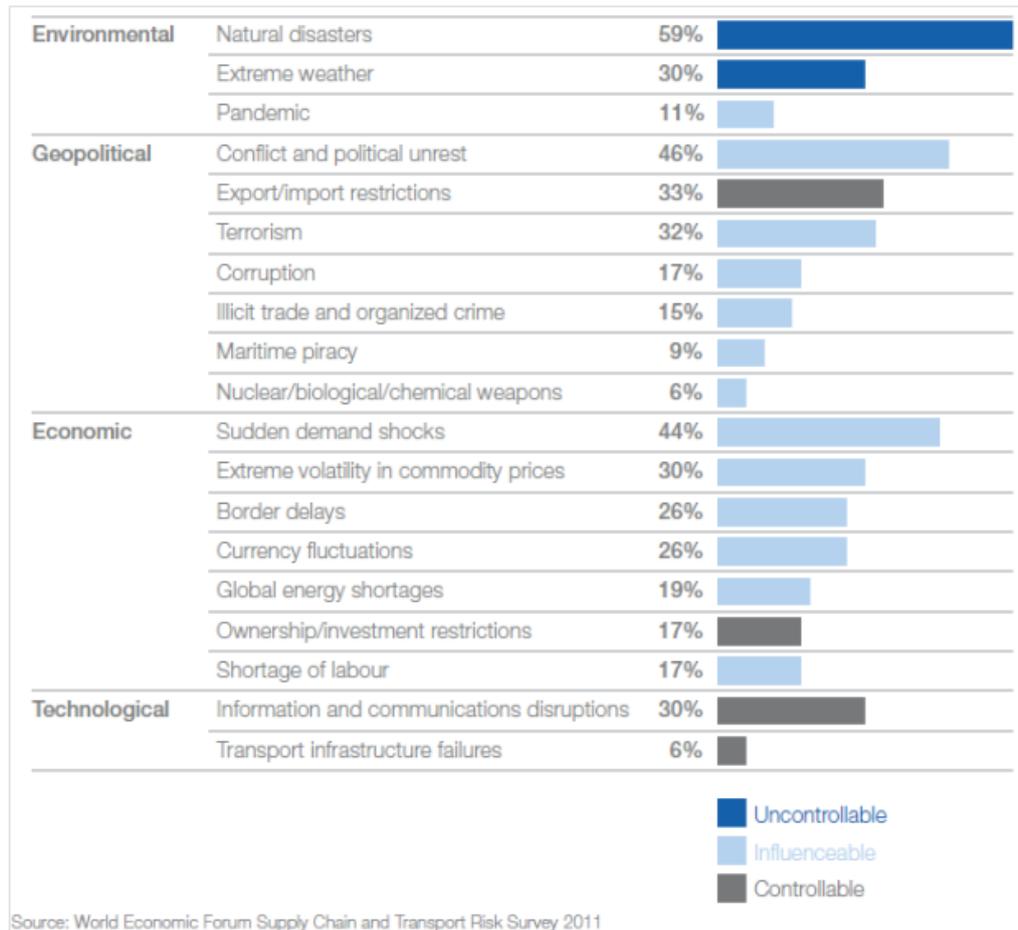


Figure 9: Triggers of global supply chain disruption

Any one or combination of these risks may affect the potential for supply chain disruption for a given material. In identifying potentially disruptive supply chain events IBM have found it useful to collaborate with suppliers and customers due to the limited number of data points a single organisation holds and to ensure the joint risk planning process is valuable to all parties (IBM, 2008).

In response to the various supply chain risks, a number of mitigation and management approaches have been adopted (US Resilience Project, 2011; Tang, 2006):

- Taking a holistic approach – looking at the whole supply chain system not just individual parts.
- Integrate internal business systems, specifically supply chain management, procurement and risk management.

- Exchange information between risk professionals in different functions – supply chain, procurement, quality assurance or risk management – to identify trends.
- Develop business continuity plans and request the same of suppliers.
- Understand your suppliers' supply chain and risk management plans; scrutinise suppliers' practices through structured audits, including incentives and penalties if necessary.
- Integrate risk management considerations into the design of the supply chain.
- Maintain clear communication of issues and events across their organisations.
- Create clear benchmark metrics of key performance indicators (KPIs).
- Build flexibility into supply chains to deal with changing market conditions and cost volatility.
- Improve visibility/ transparency through collaborative planning with suppliers.
- Incorporate risk management into supply chain planning and use IT to monitor and act on disruptive events.
- Source alternative or substitute products or components.
- Relocate or diversify production, suppliers and transportation systems.
- Maintain adequate insurance for interruptions, this should extend beyond physical damage to cover other risks.

In the highways sector the salt shortage experienced in the winter of 2009-2010 is a good example of a critical material experiencing supply chain shortages. The Winter Resilience Review (Quarmby, 2010) made a series of recommendations to secure the supply of road salt and its effective use:

- Increasing the national stocks of salt.
- Making more economical use of salt.
- Secure greater flexibility of output from the two UK based suppliers.
- Establish a national monitoring programme to ensure adequate salt stocks are provided in the right place.

In 2010/2011 the Highways Agency commissioned Halcrow to undertake a review of the 2010/11 winter season so as to assess the problems encountered with regard to the import, allocation and distribution of salt. Lessons learnt are recorded in the report with recommendations for the forthcoming winter seasons. The following mitigation measures are recommended by the report (Halcrow, 2011):

- Allocation: salt suppliers to share their delivery allocations in advance of strategic allocations to guarantee authorities in greatest need receive some domestic salt.
- Storage: Implement new guidance received from Salt Union on stockpiling and sheeting.
- Economics: The HA to consider remuneration rather than re-supply as its default policy when lending salt to other organisations.
- Delivery: better understanding of vehicle capacities and delivery notes to be provided and collected as part of the invoicing process.
- Invoicing: full local authority details to be obtained.
- Surveying: stockpile referencing to reduce errors in surveying and invoicing.

These responses from other sectors as well as the responses to improve resilience in the supply of road salt may be appropriate management responses for critical materials which will be investigated as part of this project.

In addition to the various supply chain risks highlighted above inadequate infrastructure to deal with the waste products may also have implications for material criticality. This is especially relevant to the electronics market, where without adequate infrastructure to deal with the waste products in a resource and economically efficient manner the full value of waste materials may not be recovered. Where high value materials are lost or 'down-cycled' in the end of life disposal or recycling processes this may add additional pressure to materials criticality, at a local scale this can be true of high specification aggregates used in road surfacing.

The Highways Agency's Procurement Strategy (Highways Agency, 2009) sets out the Agency's approach to dealing with risk through a structured approach comparing risk and value in their decision making process.

The segmentation model presented in the strategy (Figure 10) suggests management approaches for the various risk levels. These transferable approaches may be relevant management responses for criticality and will be investigated as part of this project.

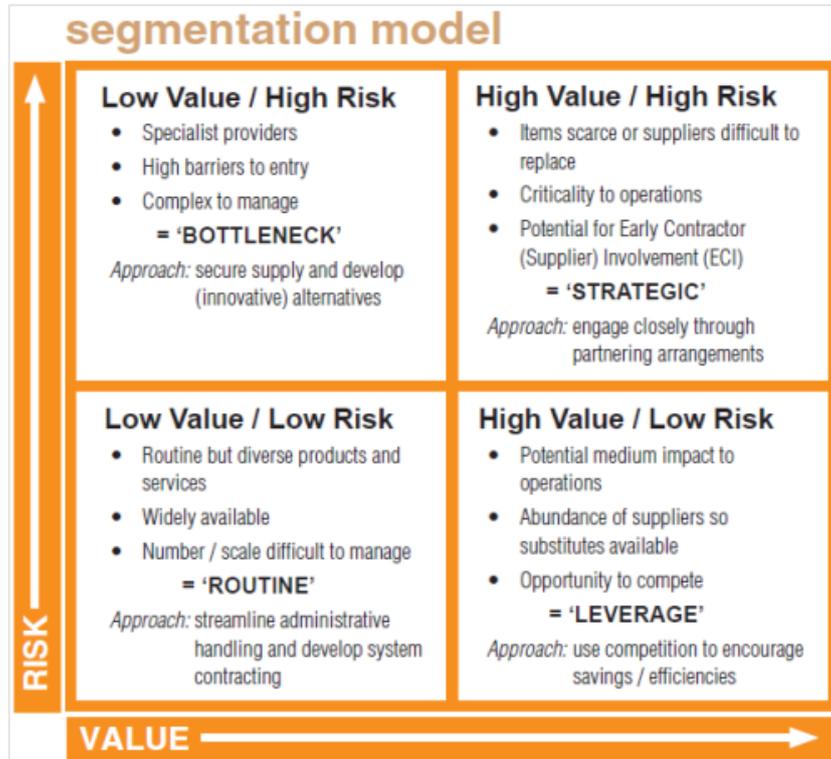


Figure 10: Segmental model for risk management (Highways Agency, 2009)

In addition to the segmentation model, the Procurement Strategy sets out the Agency's 'category management' approach to aggregate common categories across the Agency's spend. This is intended to enable the HA to work closely with existing suppliers to generate value, efficiencies and improve management processes.

Summary

- Consideration of asset management and supply chain management risks should be integrated with the business decision making process.
- Risks should be considered in a holistic approach considering multiple criteria alongside each other.
- A risk-based, outcomes focused approach to asset management optimises performance against serviceability indicators with the lowest cost of ownership.
- Mitigation and management approaches used to manage asset management and supply chain risks may be applicable in managing material criticality.
- Risk management should be an iterative process of continuous improvement.

7 Future highways infrastructure

There are myriad innovations and technologies which could potentially change the future of highways transportation and many approaches attempting to categorise them and the drivers and barriers that will affect their ability to change current practices (Highways Agency, 2009; Foresight Vehicle, 2004). The Technology Strategy Board (TSB) and the Engineering and Physical Sciences Research Council (EPSRC) fund and work on a wide range of research and development topics connected to the highways. Within Europe, the Forum of European National Highway Research Laboratories (FEHRL) acts as a focal point for collaborative research between 30 national research and technical centres including the UK's Transport Research Laboratory (TRL)

The Forever Open Road (Lamb & Collis, 2011) is the flagship research programme of FEHRL, and has been placed at the core of its fifth Strategic European Road Research Programme, published in 2011, (SERRP V). The Forever Open Road is a visionary concept of the next generation of roads; and redefines how roads will be designed, built, operated, maintained and ultimately replaced in the future. It recognises and integrates innovation in infrastructure, vehicle technology and Information and Communication Technologies. The Forever Open Road has three key elements:

- The Adaptable Road – focussing on ways to allow road operators to respond in a flexible manner to changes in road users' demands and constraints – it implies new construction methods, such as prefabrication and roads that can repair and clean themselves.
- The Automated Road – focussing on the full integration of intelligent communication technology applications between the user, the vehicle, traffic management services and the road operations.
- The resilient road – focussing on ensuring service levels are maintained under extreme weather conditions.

Whilst visionary in concept, the Forever Open Road is not purely aspirational, indeed many of the technologies it proposes have already been, or are currently being developed in research programmes across Europe. Should it ultimately be realised, fully or partially, then the Forever Open Road will provide both solutions and challenges in terms of material criticality.

If the Forever Open Road is compared to the latest generation of motorways then the differences start to become apparent. First and foremost, the ability of the Forever Open Road to self-heal and be more resilient to extreme weather conditions would vastly improve on the current durability of road pavements and therefore decrease bulk material demands, namely those of high performance aggregates and bitumen. However, the automated road, a schematic of which is presented in Figure 11, will place a greater emphasis than that which currently exists on sensors, ICT and other electronic systems, such as those used to capture energy (e.g. solar panels). In

material criticality terms, this is likely to mean a higher demand on the reserves of rare earth elements and copper, the issues with which have already been introduced in Section 3. However, the balance maybe redressed to some degree by in-car ICT, that is to large extent is already present in vehicles, being given greater capability in the future to replace the need for overhead variable message signs in the future.

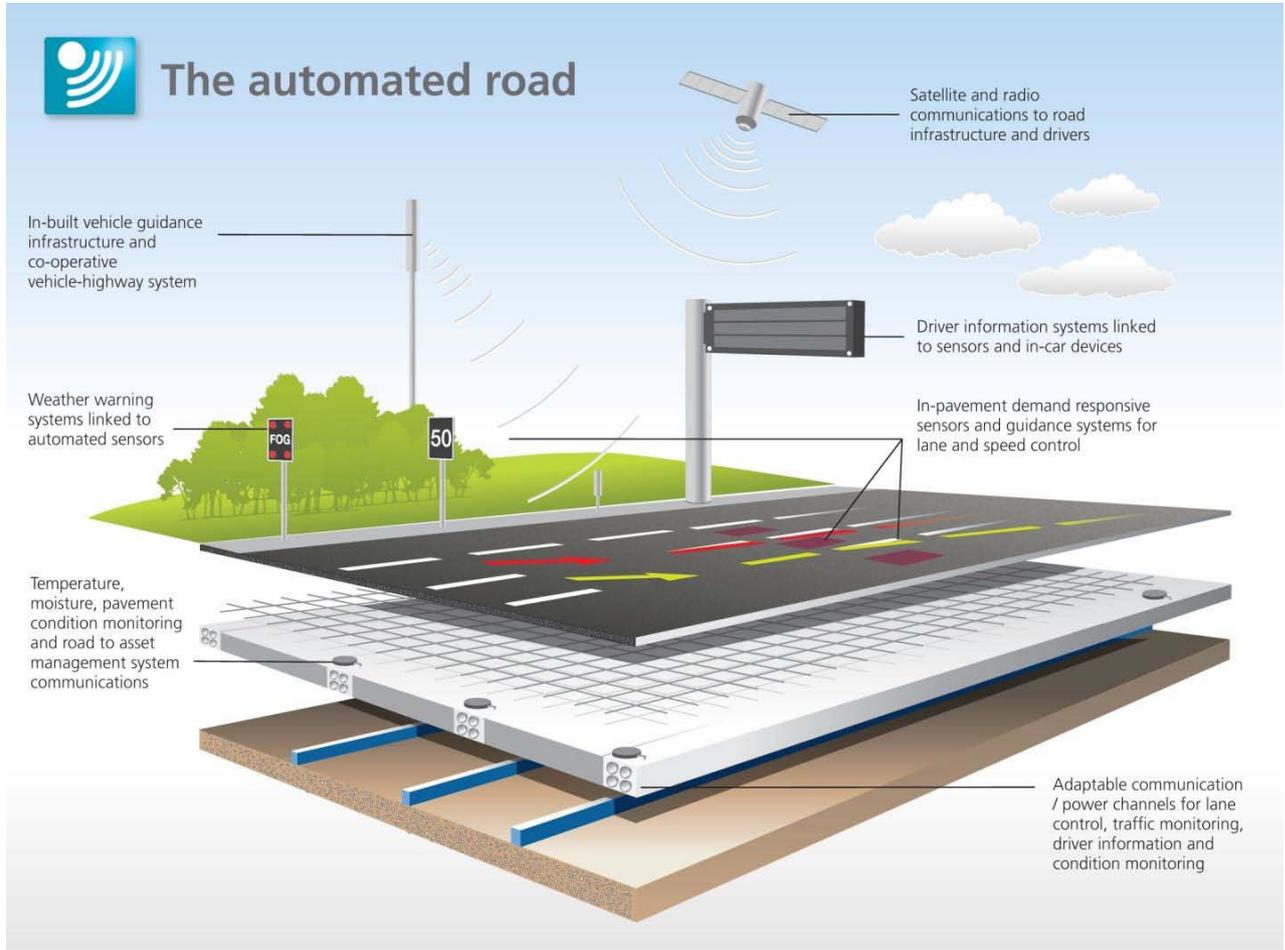


Figure 11. The automated road – part of the Forever Open Road concept

With relevance to the criticality of materials, there is broad recognition that there are expected incremental and radical innovations in the technology that underpins highway construction and material composition, functionality and communicative ability, maintenance processes and programmes, and in-car ICT.

Incremental changes in materials will likely see recycled plastics, other aggregates and lower environmental impact replacements to bitumen incorporated into their structure. There are also new technologies which aim to increase repair efficiency, the lifecycle of existing surfaces and reduce resource use such as induction healing of asphalt, and 'road on a roll' (RollPave).

The road surface itself might see innovations such as the incorporation of glow in the dark paints that can 'light' the highway without the need for

overhead lighting and paints that react to extreme weather to warn drivers of conditions (Government Technology, 2012). There are new concrete prefabricated sections of road that contain infrastructure services such as drainage channels and communication cables (Modieslab) to ease construction times and costs whilst radical changes could see roads composed of a collection of solar panels or have the capability to generate energy from piezoelectric sources (Lamb & Collis, 2011).

Real time data availability and management is already increasing throughout the UK highways network (Department for Transport, 2008). Innovations to in-car communication and location technology such as Locata, a ground based positioning system with greater accuracy and reliability than GPS, and autonomous driving capabilities may mean that external ICT infrastructure becomes less relied upon. Alternatively, it could signal the demand for greater centralised networks. Near Field Communication (NFC) devices also have the potential to be useful in providing data on asset condition and detail on materials used in assets on site.

All of the above potential changes to the structure and function of the highway network will have consequential knock on effects to the infrastructure required to support the highways network and hence will effect material use, demand and flows. Reliable predictions of the effect in terms of material criticality under current data constraints are impossible.

In addition to the potential changes to highways infrastructure identified other infrastructure will also evolve and may impact on material criticality for highways as demand changes. The changing nature of highways infrastructure may create new or stronger dependences on other infrastructure, such as the power grid or communications networks. Also interdependencies may develop where infrastructures are combined to enable more efficient provision of services.

A robust criticality framework combined with increased availability of data relating to material use and flow would facilitate the construction of systems maps and stock and flow models. This would allow scenarios of technology implementation to be tested and would give a range of reliable predictions of material criticality in a way that is currently not possible.

Summary

- There are a number of incremental and radical innovations in the technology that underpins our highways infrastructure that are set to alter the flow and use of and demand for a wide range of materials, such as the greater use and reliance on technology to inform, plan and manage journeys and traffic flows.
- Emerging technologies that are likely to be incorporated into the next generation of highways have the potential to both alleviate and intensify some material criticality related issues.
- Material criticality should be a key consideration in the development of new highway technologies. This will give scope for material substitution and alternative approaches to be considered.
- Currently there is insufficient data available and no adequate process or framework devised to allow the accurate prediction of material criticality based on future innovations and technologies within the highways network.
- With further research into the lifecycles of materials, mapping of the systems that effect and are affected by material criticality and development of robust processes and frameworks, accurate predictions should become achievable.
- The consideration of material criticality related to highways infrastructure and the delivery of the Highway Agency's core functions cannot be considered in isolation but must understand dependencies with other infrastructure and also the vulnerabilities associated with these interdependencies.

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