Investigation into the Development of a Framework for the Identification and Appraisal of Infrastructure Interdependencies with Application to Critical UK Infrastructure: Case Study Report for Infrastructure UK and the Department for Transport.

Review of Potential Infrastructure Interdependencies in Support of Proposed Route HS2 Phase 2 Consultation

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Disclaimer

This report comprises a review of publicly available documents, plus additional data and information gathered at a workshop held on the 14th of March 2013 at the Department for Transport, Great Minster House, and a follow on meeting held on the 11th of April 2013 at the same location. The views and recommendations expressed in this report are solely those of the authors and do not represent Government policy.

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Contents

List of Figures

List of Tables

Executive Summary

This report details the application of an Interdependency Planning and Management Framework (IPMF) [1] explore engineering-based opportunities and benefits for Phase 2 of High Speed 2 (HS2). The IPMF framework has been developed through the collaboration of The Systems Centre at the University of Bristol, and The Omega Centre and The Bartlett Faculty of the Built Environment at University College London. The project to develop the framework and apply it to the HS2 Phase 2 was initiated by Infrastructure UK, part of HM Treasury.

The aim of this case study was to identify inter- and intra-sector interdependencies between the planned HS2 Phase 2 project and the water, Information and Communication Technologies (ICT), energy and transport sectors and their infrastructure systems; complete a rapid evaluation of any potentially beneficial interdependencies identified; and thereby provide an indication of the value of incorporating interdependency planning within the HS2 Phase 2 consultation.

The principles of the framework, along with some of its associated tools were applied in a workshop held on the 14th of March 2013 at the Department for Transport, Great Minster House. It was facilitated by The Systems Centre, University of Bristol. A follow-up meeting was held on the 11th of April 2013 to capture any additional thoughts on the output from the first. The workshop outcome was reported in a first draft report, and this final report compiles all aspects of the case study including feedback on the prior draft workshop report.

The four interdependencies with the greatest potential benefit for UK infrastructure were identified by consideration of HS2 Phase 2 within the wider network of national and local infrastructure systems, and comprise:

1. **Using the HS2 Phase 2 corridor to provide additional electricity distribution capacity into Sheffield and Manchester:** Combining HS2 Phase 2 with projects to enhance electricity distribution would consolidate and reduce visual blight and disruption during construction, though there would be issues over ownership, legislation and regulation. Economically, a single integrated project may be favourable as the total cost would be less than for two separate projects (e.g. for planning, consultation and tunnelling), and it would support and align increased economic activity in these regions. In social terms, city regions are expected to grow with the expectation that HS2 would also contribute to stimulation of population growth. This in turn means an increased electricity demand and a requirement for additional energy infrastructure. Technological impacts are expected to be minimal, though conductor technology may have advanced by the time of installation, increasing capacity as a matter of course. However, additional and diverse routing of the electricity network could improve overall resilience [2].

2. **Using the HS2 Phase 2 corridor to provide the capability for intra- regional water transfer:** From an economic perspective the pricing principles for trading across water regions is in place and such an approach could provide a cheaper alternative to other water resource development options such as long distance pipelines. For example, some water supply regions tend to be weakest at their extremities, so transporting water from neighbouring areas with an excess of water resources would be rational from a whole

sector standpoint. It would also add to the resilience of the total UK water supply network and from an environmental perspective it could help regulators balance abstraction licensing against supply needs. The concept of water transfer between water companies and water supply zones has been explored by Water UK, and the United Utilities 55km, £120m bi-directional pipeline between Manchester and Liverpool (West-East Link Main) is an example of the recent development of this type of infrastructure [3].

3. **Using the HS2 Phase 2 corridor (and associated construction) to provide the capability for additional flood protection:** Such an approach could be of significant socio-economic value in terms of enhanced flood protection for householders and businesses in the affected flood plains, as being of interest to insurers and government agencies such the Environment Agency. Politically it would also be attractive if the HS2 Phase 2 project brought further benefits beyond the public transport sector. While the proposal is technologically achievable, it would come at additional costs, and furthermore the dynamic effects in flood plains are uncertain, and would combine with those uncertainties due to climate change and land use changes. Overall the workshop conclusion was that any scheme would be likely to create an overall positive benefit for the UK. It was noted that a report by Engineering the Future [4] supports the potential for the use of railway embankments as flood defences, whereas a joint report by DEFRA and the EA [5] indicates that *existing* rail embankment designs are not fit for flood defence purposes, although in some circumstances they may provide a partial barrier.

4. **Using the HS2 Phase 2 corridor to provide additional capacity for the distribution of ICT infrastructure (e.g. fibre optic cables):** The principal value would accrue by helping achieve UK national connectivity targets with less disruption than installing new separate ICT infrastructure. This option could offer diversity to the UK's ICT network, and may in the short term simply require a level of provisioning for future installation of ICT hardware. Wayleave agreements along the HS2 route would need to be established between interested parties, along with maintenance and access arrangements. Economically this opportunity could provide an efficient route, with low latency making the relocation of data centres outside London more attractive, and this in turn could create new job opportunities outside of the London area. It could also be used to boost rural economies along the HS2 route. A countervailing view was that the HS2 project may be too late to assist in achieving UK connectivity goals, and by the time the project is operational, the need for additional fibre cables (particularly for domestic use) may have been superseded by alternative wireless technologies such as 4G. Further support in the literature for this interdependency includes the report by Frontier Economics [6] which explicitly suggests that other utilities such as 'super-fast broadband' should use rail corridors, and the OECD report [7] which proposes that transport networks include provision of a right of way for utilities to lay communication cables.

The interdependencies identified in this case study cross the traditional boundaries of infrastructure sectors. For them to be effectively considered in detail requires the HS2 Phase 2 project to be conceptualised as more than the delivery of transport infrastructure, and to identify benefits beyond the provision of additional rail capacity and reduced journey times. In such an analysis the benefits and risks need to be evaluated holistically across the entire network of national infrastructure, i.e. for the HS2 Phase 2 project coupled with the infrastructure systems of other industrial sectors.

1 Introduction

The forecasted lack of mainline rail capacity is seen as a significant issue for continued economic development in the UK, prompting Network Rail [8] to investigate the potential for capacity gaps for the "*the five 'classic line' route corridors that radiate in an arc to the west and north of London*", these being the Great Western, Chiltern, West Coast, Midland and East Coast main lines. Forecasting continued strong passenger demand and freight growth, the study concluded that new lines would be required to achieve a quantum, or step change in network capacity by 2020, and that incremental improvements to the existing mainlines could not plug the forecasted capacity gap. The study concluded that this analysis be "*used to inform the generation of new line(s) options and also the associated changes to the classic routes. Generation of options should focus on relieving the demand-capability gap on the WCML followed by the MML and ECML.*"

The High Speed 2 (HS2) rail project was therefore proposed to meet the transport demands by improving North-South links between several major urban areas, and in the first instance, was conceived as the means to deliver the 'quantum' leap in network capacity: "*High Speed 2 (HS2) provides an unparalleled opportunity to improve connectivity and increase capacity on Britain's railway. Network Rail does not see HS2 as a separate line, but rather as part of a reshaped national network.*" [9]. The starting point for this case study was this definition of the core purpose for HS2, and that this should not be compromised by any potential cross-sectorial interdependencies.

Historically the design, planning and appraisal of a large-scale infrastructure project such as HS2 has been treated as an individual technical challenge, with only sufficient integration as is required to complete the project aims. The Council for Science and Technology [10] however recognises that in reality national infrastructure is more akin to a network-of-networks. This is reflected in the National Infrastructure Plan 2011 [11] which noted that the UK's approach to infrastructure had thus far been fragmented, adding that: "*opportunities to maximise infrastructure's potential as a system of networks have not been exploited*".

The National Infrastructure Plan (NIP) describes interdependency as arising "*where the impacts of change in one network are felt in other networks*". A report by the World Economic Forum suggests "*Infrastructure is not functional unless it is correctly connected to other infrastructure. Therefore, inter-linkages and Interdependencies with other infrastructure networks should be considered when developing new projects.*" They add that "*governments should consider whether infrastructure networks can be bundled together. For instance, it may be more cost-effective to lay gas and water pipes in the same trench rather than in two separate trenches. However, the cost savings need to be balanced against the higher risk*". This highlights the potential for two types of interdependency:

1. Those necessary for the infrastructure element to fulfil its desired purpose;
2. Those which are optional, but may improve efficiency or deliver additional benefits.

Furthermore, research by UCL's Omega Centre [12, 13] has found strong evidence that large-scale infrastructure is often developed via a complex programme of on-going investment, delivered over time and in different contexts. These infrastructure programmes frequently become critical '*agents of change*' with multiple spatial, economic, environmental and other implications, including the transformation of the context into which they are placed. As such they comprise a wicked planning problem characterised by incomplete, contradictory and changing requirements, to which there is no obvious and assured solution. In addition, the researchers found that such 'agent of change' functions in the UK are often evolutionary in nature, emerging from piecemeal developments over long periods of time, this being attributed by the authors to a lack of clear strategic policy.

High Speed 2 is to proceed in two phases: Phase 1 is set to run from London to the West Midlands and is expected to begin construction in 2017. The preferred option for Phase 2 is a Y-shaped network made up of two lines running north of Birmingham: one to Manchester and one to Leeds [14, 15]. Infrastructure UK identified HS2 Phase 2 as a suitable case study for the review of potential interdependencies, with the aim of establishing evidence to support the Department for Transport (DfT) when scoping the HS2 Phase 2 consultation, and to identify opportunities to build on the economic case by recognising the transformative 'agent of change' nature of this particular Mega-Transport Project.

The approach underpinning this review of interdependencies was to broaden out conventional project-focused planning and engineering considerations. Instead, using an 'open systems' approach, the assessment of interdependency looked for opportunities from the interaction of the HS2 Phase 2 project with the wider system of utility infrastructure networks and national policy objectives, and to explore the possibility of unanticipated outcomes as part of a future 'emergent order'. To achieve this, the workshop implemented elements of a proposed Interdependency Planning & Management Framework (IPMF) which has been developed by the Systems Centre at the University of Bristol, and The Omega Centre and The Bartlett Faculty of the Built Environment at University College London [1].

This framework is founded on a holistic, open systems-based approach that views critical infrastructure as a system of networks that is created iteratively in response to evolving stakeholder purpose. A key principle underpinning this is that effective and efficient 'stewardship' of infrastructure requires a shift away from an individual asset management perspective. Instead it calls for a wide range of institutions and enterprises to collaborate in developing a coherent framework of policies, plans, processes and institutions to guide infrastructure investment and planning. In this way the IPMF is intended to facilitate the collaboration of infrastructure stakeholders in the identification and evaluation of existing and innovative infrastructure interdependencies, highlighting opportunities for additional value and more effective risk management.

The process of identifying interdependencies was completed during a structured workshop involving a diverse group of stakeholders from the transport, energy, ICT and water sectors, working alongside academics, representatives from HM Treasury, Infrastructure UK and those involved in the HS2 Phase 2 project. The first workshop was held on the 14th of March 2013 at the Department for Transport, Great Minster House. It was facilitated by The Systems Centre, University of Bristol. A follow-up review meeting was held on the 11th of April 2013 to capture any additional observations and evidence.

The IPMF used a matrix-based approach to support the identification and classification of interdependencies: firstly between high-level Government policies and elements of the HS2 Phase 2 infrastructure; and secondly between the infrastructure needs of the transport, energy, ICT and water sectors and elements of the HS2 Phase 2 infrastructure. Workshop delegates then went on to evaluate in broad terms the benefits or costs of the key interdependencies using a PESTLE-based tool (see Section 2.3.2), as well as identifying where additional evidence to support this evaluation could be found.

The workshop outcome was reported in a first draft report, whilst this final report compiles all aspects of the case study including feedback on the prior draft workshop report and additional learning from the IPMF development project. Section 2 outlines the workshop methodology and tools used to support the review of interdependencies. Section 3 details the application of the framework in the context of the HS2 Phase 2 project, and goes on to describe the finding from workshop and follow on meeting. A second aim of this case study was to assess the effectiveness and applicability of the IPMF as a means of facilitating the identification and evaluation of interdependency, and an evaluation of the workshop results is therefore presented in Section 4. Section 5 presents the final conclusions from this case study application in the light of the lessons learnt throughout the development of the IPMF.

2 Interdependency Workshop: Methods & Tools

2.1 Overview

This case study was conducted at two workshops, both involving participants from four different infrastructure sectors: Energy, ICT, Water and Transport. The participants represented a broad set of stakeholders with interest in the HS2 project, as well as in potential interventions and impacts that might result from engineering interdependencies.

The format of the first workshop provided the means to engage stakeholders and explore the context and boundaries in an open-systems manner. It also provided access to a broad knowledge-base on the policy context across multiple infrastructure sectors.

For the first workshop session the participants were split into four groups based on the infrastructure sectors they represented. A matrix-based approach (see below) was used to structure the identification of interdependencies and engage stakeholders in considering engineering innovative interdependencies with the potential to enhance the core HS2 project proposal.

The second workshop session provided an opportunity for each group to share findings, to establish known evidence and arguments for and against the further consideration of those interdependencies identified earlier, including a broad valuation of their costs and benefits. This process considered the political, environmental, social, technological and economic (PESTLE) factors affecting the interdependencies, and identified sources of evidence.

The following two sections outline the overall workshop method in detail, and the tools used to identify and evaluate the potential interdependencies. This is followed by a discussion of the workshop output and the most significant conclusions, including those interdependencies identified as being of most significance for further appraisal.

2.2 Workshop Method

The workshop implemented elements of the Interdependency Planning and Management Framework (IPMF) shown schematically in Figure 1. The overall challenges of engineering infrastructure and addressing issues of interdependency requires an approach able to handle a network of potentially disparate systems, including ‘soft’ socio-economic aspects. In Figure 1 this is conceptualised as a wicked problem: that is to say it is multifaceted with no definitive formulation and no absolute right or wrong answer. Through understanding the purpose and problem space an iterative process of structuring, measurement and appraisal is used to develop understanding both of the challenge and its potential solutions. The format of the workshop was intended to facilitate this iterative form of inquiry across both the problem and solution spaces.

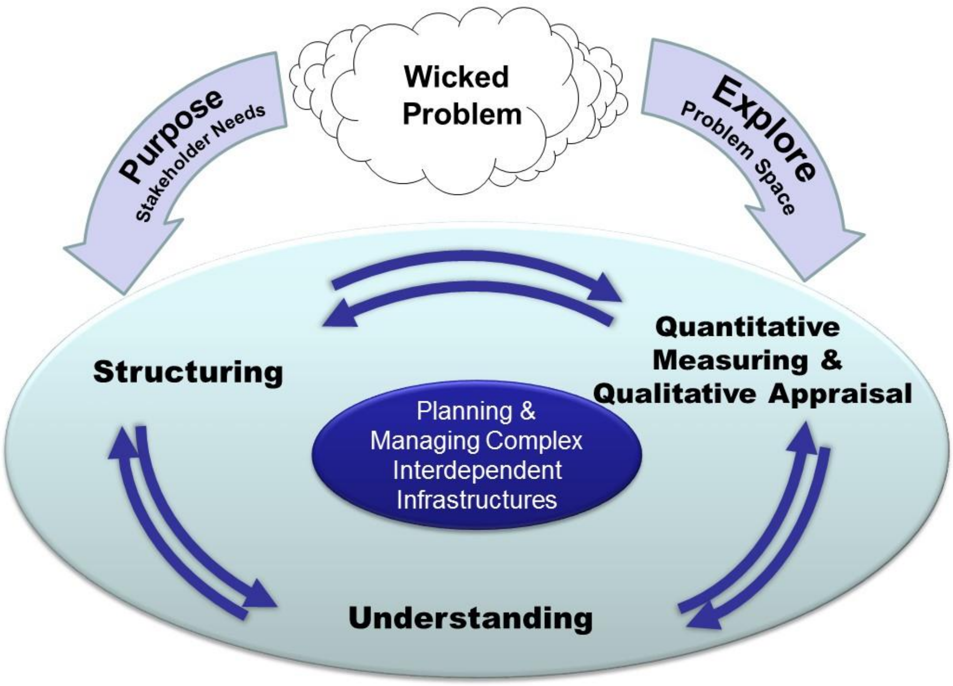

Figure 1 Problem Structuring Underlying the Interdependency Planning and Management Framework

Session 1: Domain-Based Identification of Interdependencies

The participants were split into four domain-based working groups (Energy ICT, Water and Transport). Within these groups a matrix-based approach (see below) was used to guide the identification and structuring of potential interdependencies between the elements of each sector-based infrastructure and the HS2 Phase 2 project.

Session 2: Feedback

The second session provided an opportunity to share the findings from the first session amongst the groups, developing collective understanding. This allowed for an open discussion of opportunities, risks and additional interdependencies. The participants were also encouraged to consider secondary interdependencies which might exist between the Energy ICT, Water and Transport sectors.

Session 3: Evaluation of Interdependencies and Evidence Sources

For the final session, the participants reconvened into their sector-based groups in order to discuss the evidence for and against the further consideration of each interdependency identified during the first session. To ensure a broad evaluation this process encouraged the consideration of political, economic, social, technological and environmental (PESTLE) factors. The participants were also provided with the opportunity to make any uncertainties explicit.

Follow-Up Review Meeting

The workshop participants were provided with the output from the first workshop, and given an opportunity to reflect on it before a review meeting was held one month after the first. This was in order to allow the participants to consult within their organisations and evaluate the identified interdependencies, highlight any interdependencies that might have been missed in the first workshop, and to provide additional evidence or case studies.

2.3 Workshop Tools

The workshop used two tools to implement the Integrated Planning and Management Framework (IPMF) and support the identification and evaluation of potential interdependencies. These are described below.

2.3.1 Matrix-Based Interdependency Structuring Tool

The matrix-based tool has been developed from the N-Squared (N^2) Chart tool created by Lano [16] for the analysis of interfaces and relationships. It gets its name from the fact that for a system model defined by an N by N dimensioned matrix, then there will be N^2 cells (or boxes) in which to represent the sub-systems and their interactions. Lano describes this as "*a visual aid which can be effectively employed to communicate functional or physical interface and interrelationship information to a large group and/or mixed discipline audience in a very short time period*" and that "*it provides the user with an effective tool for the definition, tabulation, design and analysis of these interfaces.*"

At its most basic, the N^2 Chart comprises a matrix with the principal system functions represented along the leading diagonal of the matrix, i.e. Function 1 (F_1), Function 2 (F_2), … to Function N (F_N), leaving the remaining off-diagonal boxes to represent the interactions between them. This is demonstrated by the example shown in Figure 2.

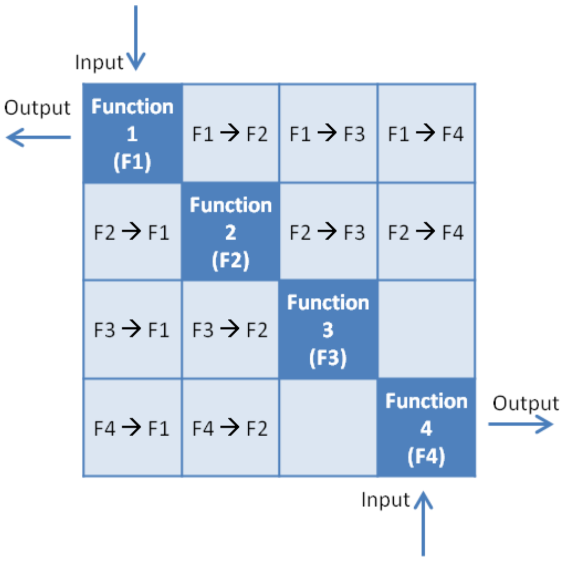

Figure 2 Example N-Squared Chart (after Lano, 1979)

In this example, the principal system functions F_1, F_2, F_3 and F_4 are represented by the darker boxes running from the top left corner to the bottom right corner. These for example could be services provided by the major infrastructure systems such as public transport or drinking water supply. The off-diagonal boxes show the interrelationships between these functions, and in the implementation of the IPMF these comprise the interdependencies between for example infrastructure systems, the services provided by industrial sectors, or policy objectives. In its original form these off-diagonal boxes are conceived as outputs and inputs, such that the box labelled "$F_1 \rightarrow F_2$" shows that an output of Function 1 becomes an input to Function 2. The squares in horizontal rows therefore become the outputs of the function in that row. The squares in the vertical columns show the inputs to the function in that column.

In the workshop, the matrix tool was used to establish the principal systems and policies under consideration for each sector, and to record these along the leading diagonal of the matrix (i.e. in the dark boxes). It was then used to structure a systematic consideration of the potential for interdependency that might exist or be engineered for each of the off-diagonal boxes.

When using this approach to represent the interdependencies between multiple infrastructure projects or policies, it is important to establish a coherent and representative model of the most significant inputs and outputs of the infrastructure systems under consideration and also any additional external systems on which there may be a shared dependency. For example, two projects might have interdependencies because they are being developed by the same owner or because they are co-located in the same geographical space. Additionally, two projects may be interdependent if they have similar capabilities and hence fulfil the same social or market need, and this may be true even if the system implementations are markedly different.

A further complexity to take into account is to recognise that major projects, for example Mega-Transport Projects (MTPs), are likely to comprise multiple layers of policy delivery, project activities and infrastructure components. Even when policy-led overall, it is unlikely that there will be a well-ordered, top-down alignment between these layers, but a more complex mapping with some projects being perceived as more significant than 'lower level' policies as illustrated in Figure 3 (below).

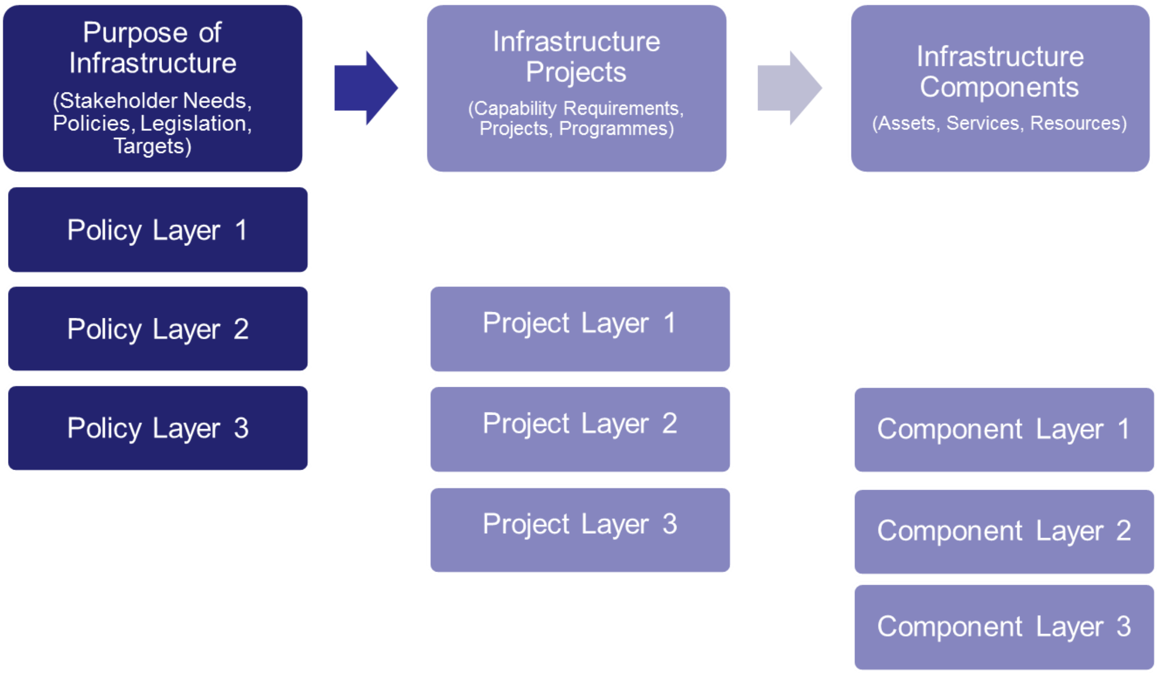

Figure 3 Mega-Transport Projects Represent Complex Developments Comprising Layers: Policy Delivery, Project Activities and System Components

2.3.2 PESTLE-Based Interdependency Valuation Tool

When an existing or theoretical interdependency was identified between two system elements, the participants were encouraged to consider the range of different forms the interdependency could take. Several methods have been proposed to capture the different types of interdependency specific to infrastructure. The tutorial suggested four broad types drawn from those suggested by Rinaldi *et al*. [17], Ventura *et al*. [18], the National Infrastructure Plan 2012 and a report on infrastructure interdependency by Frontier Economics [6].

These four types of interdependency discussed during the workshop are Physical (e.g. a transfer of material between elements, or one element's physical reliance on the function of another), Digital (e.g. a transfer of information), Geographic (e.g. co-location) and Organisational (e.g. linked through a mechanism of finance or governance). It is useful to also evaluate whether it provides positive benefits, additional risks, a neutral impact or unjustifiable costs. It is also possible that the effect of the interdependency may be unknown or involve a high degree of uncertainty.

The third workshop session utilised a standardised table for the evaluation of the interdependencies identified in the first session. The process is based upon the PESTLE framework, encouraging participants to consider the evidence for or against each interdependency in terms of political, economic, social, technological and environmental factors. It also allows for any uncertainties to be explicitly captured.

The final steps in this process require the participants to assess whether the interdependency is of positive, negative, neutral or uncertain impact, and indicate a rough order of magnitude for the financial impact of the interdependency.

3 Workshop Results

This section presents those existing or potential interdependencies which were identified by participants for the proposed HS2 Phase 2 project and its interaction with the policies and projects selected for the five selected infrastructure sectors. This cannot comprise a complete list of all plausible interdependencies due in the main part to the limitations imposed by the workshop conditions, i.e.:

1. The time limitations placed on the three workshop sessions;
2. The focus on identifying beneficial interdependencies, i.e. opportunities;
3. The constraint imposed by assessing interdependency for only four pre-selected engineering sectors;
4. Limiting the consideration of interdependency to that arising between a maximum of six systemic features for each sector;
5. The extent of the collective knowledge and perspectives of the workshop participants.

The application of the IPMF at these workshops resulted in the identification of 24 interdependencies between the HS2 Phase 2 project and other infrastructure sectors with the potential to enhance the value of the core project proposal. Of these, four, were prioritised and recommended by the workshop participants for further evaluation to identify evidence for or against these interdependencies.

Adopting an 'open systems' perspective allowed the stakeholders to take a broader view of the HS2 Phase 2 project, and look beyond its core purpose of delivering a quantum change in transport capacity. Although there remained a strong perspective on the provision of a physical corridor along the proposed HS2 route, the 'open systems' approach also facilitated the identification of inter-sector interdependencies, and arguably a conception of the project as a potential 'agent of change' within non-transport infrastructure sectors.

It would be neither reasonable nor possible to conclude that the interdependencies identified at the workshop are the most important, whether measured by overall economic value, resilience or environmental benefits. The form and detail of evidence available was also limited to overall qualitative assessments of benefit, supported where possible by pre-existing quantitative data. However, it is possible to conclude from the domain knowledge of the participants in the workshop, that the beneficial interdependencies identified are plausible and worthy of further evaluation.

The following sections provide a detailed account of the workshop findings.

3.1.1 HS2-ICT Sector Beneficial Interdependencies

The set of beneficial interdependencies identified for the Information and Communication Technologies (ICT) sector and the potential for beneficial interaction with the HS2 Phase 2 project are presented in the matrix mapping set out in Figure 4 (below).

	1	2	3	4	5	6
A	Core Networks	-	-	-	-	Provide resilience for HS2 control systems
B	-	Backhaul	-	-	-	-
C	-	-	Access Network	-	-	-
D	-	-	-	Mobile & Wireless	-	Provide communications for passengers
E	-	-	-	-	Data Centres	Enhance passenger information & booking
F	Provide alternative route for additional network	Provide alternative route for additional network	Enhance connectivity in 'remote' areas near HS2 spur off points; Provide access at road/rail crossings	Provide shared or additional masts and connections for mobiles	Provide potential for new locations; Provide opportunity for low latency connections (via straight route)	**HS2 Phase 2 Rail Line & Route**

Figure 4 HS2–ICT Sector Opportunities

There is potential for the HS2 Phase 2 route to provide an additional corridor for the ICT access network, to enhance links from subscribers to their service provider. Benefits to the core and backhaul (intermediate) parts of the network were not ruled out.

From a political and legal perspective integrating the Wayleave permissions for HS2 and an ICT project may be beneficial due to the potential long-term cost savings in legal and planning processes. There may also be reduced project management and engineering costs, as well as fewer environmental impacts from building ICT infrastructure along the HS2 corridor. For example, maintenance access provided to HS2 may also provide maintenance access for any communications cables routed through relatively remote areas.

Overall, any additional capacity integrated with the HS2 route could increase competition within the ICT sector and deliver better services to locations along the route, including rural areas. Providing additional capacity also means that latency (time delays) across the whole network could be reduced, opening up the possibility of relocating finance and data centres to boost regional economies and associated jobs.

From a technical perspective, there is a degree of uncertainty over the future of communication networks and what might be the preferred technologies to deploy. For example, the expansion of high bandwidth connectivity through other means such as 4G mobile signal coverage and similar technologies might suggest that such additional fixed physical capacity may be unnecessary or may become operational too late to be beneficial. However, set against this, and from a 'whole system' perspective, a diversity of routes and technologies enhances resilience. Therefore the provision of diversity *and* capacity in ICT provision may in itself be a compelling proposition for policy-makers, providing the costs of provisioning and installing such infrastructure are relatively low.

3.1.2 HS2- Energy Sector Beneficial Interdependencies

The set of beneficial interdependencies identified for the energy sector and its potential interaction with the HS2 Phase 2 project are presented in the matrix mapping set out in Figure 5 (below).

	1	2	3	4	5
A	**New Electricity Supply (to HS2)**	-	-	-	New nuclear power stations to meet HS2 and domestic power needs; Hydrogen powered trains
B	-	**Electricity Supply (to area around Sheffield)**	-	-	-
C	-	-	**Existing Electricity Network**	-	Assured provision and network access agreements for utility providers
D	-	-	-	**Existing Gas Network**	-
E	-	Potential to build new electricity generation and network	-	-	**HS2 Phase 2 Rail Line & Route**

Figure 5 HS2–Energy Sector Opportunities

Potentially favourable interdependencies were identified by using the HS2 corridor to locate enhanced electricity supply networks to Sheffield and Manchester, two areas where there was believed to be a local need for investment in electricity infrastructure. Clearly this principle could be applied up and down the infrastructure corridor, with 'passive provisioning'[3] an option where future installation needs are ill-defined or not known.

[3] 'Passive provisioning' is to plan or design of a system, such that it has suitable accommodation(s) to allow for the design and installation of auxiliary systems or components in response to future, possibly unknown, societal needs or requirements. Examples include leaving sufficient capacity or space in a design for a retrofit or system upgrade, or to allow further additional services or utilities to be installed alongside the core infrastructure. It could also be to establish a broader legal framework of consents, thereby not foreclosing on the future installation of additional equipment and services not specified at the time of the primary core project.

A further benefit of integrating energy and transport corridors could be to make such projects more politically and financially attractive. Tangible benefits could include reductions in total planning costs when compared with two separate schemes, savings in legal costs such as securing Wayleave agreements, and a consolidation, if not reduction, in visual blight. However, set against this was a concern that coordinating cross-sector infrastructure development would create complications and challenges in terms of ownership, and rights of access for maintenance and regulation.

If HS2 changes patterns of economic activity as was suggested at the workshop, then there is an expectation that patterns of demand for electricity will change in line with this. Piggybacking the provision of electricity off the HS2 route was proposed as a cost effective approach to the provision of the additional capacity needed if new levels and distributions in demand are to be met. Again containing the extent of land take and constraining the disruption and visual impacts to lie within the HS2 corridor provides an opportunity benefit. The principal uncertainty identified by the workshop was that electricity network infrastructure is ageing, and by the time HS2 begins construction, new more efficient conductor technologies may be available for implementation.

One further interdependency identified at the workshop concerned electricity generation, where it was thought that HS2 infrastructure could be developed so as to provide a means to generate and distribute electricity albeit on a micro-scale. Although it need not feed into the national grid, it might reduce the consumption demands of operating the high speed network. This could take the form of photovoltaic cells on the roof of the train, on adjacent land or integrated with screening and sound barriers.

Finally, a range of ideas to harness energy from the turbulence created by trains passing through tunnels, recursive breaking and trackside micro-generators were also raised. In the context of sustainability, there was also a suggestion that HS2 could utilise trains with individual hydrogen-based power supplies. The technology readiness and safety of such hydrogen powered trains was debated in the workshop. Related to this is the potential for the shared corridor to be used for the distribution of hydrogen, or other gas networks, but at the cost of additional safety risks to HS2 which would need to be assessed.

3.1.3 HS2-Water Sector Beneficial Interdependencies

A number of potentially beneficial interdependencies were identified for the water sector and its interaction with the HS2 Phase 2 project, three of which were thought to be of significant interest. These are presented in the matrix mappings set out in Figure 6 and Figure 7 (below).

The first area identified in the workshop related to climate change and adaptation policy, and its interaction with the impact of changing rainfall distribution on security of water supply. The core interdependency was the potential to use the HS2 corridor also as a route for water transfer from areas with a surfeit of water and greater security of supply, to those areas of the country with less security of supply, or a deficit in water resources.

	1	2	3	4	5
A	**Climate Change**	-	May result in increased rainfall in North & decreased rainfall in South	May result in increased rainfall in North & decreased rainfall in South	-
B	-	**Flood Protection**	-	-	Affects resilience of the railway
C	-	-	**Intra-Region Transfer**	-	-
D	-	-	-	**Bulk Transfer**	-
E	-	HS2 embankments provide opportunity for flood detention storage	Provide route for pipeline to strengthen interconnections between water supply zones	Provides route for North-South bulk water transfer pipeline	**HS2 Phase 2 Rail Line & Route**

Figure 6 HS2–Water Sector Opportunities

The first option considered was to integrate the planned HS2 Phase 2 with a scheme for bulk water transfer from the North-West, along the route to the South-East, potentially also using canals. The aim would be to improve drought resilience and sustainability on a national scale [19, 20]. Although technically feasible, the workshop participants identified the following problems with such an engineering scheme:

1) That the need for bulk water transfer along the Phase 2 section of the HS2 route is not as great as for the Phase 1 section from the Midlands to the South East and as it stands, this option is no longer available due to the consultation process for HS2 Phase having been completed.
2) Implementing a bulk water transfer scheme is a significant project, added to which there is no immediate need: the water sector has established 25-year plans and water resources forecasts which indicate that a bulk water transfer scheme would be unlikely to be required in this timescale.
3) Bulk water transfer was judged to be more expensive than alternative water management options, e.g. water demand management and the development of alternative water resources such as reservoirs in the South East.
4) That pumping water would make this an unattractive option in terms of the related energy intensity and carbon emissions.
5) Pipework and pumping required to carry out the bulk water transfer might present a risk of significant disruption to the HS2 service should there be a leak or a burst pipe.

Set against this, the timescales for HS2 Phase 2 stretch beyond the period of these 25-year forecasts and plan, and there is a greater uncertainty about water resource needs beyond this 25 year time horizon. This is particularly the case when factoring in the potential uncertainty presented by climate change and water demand in the South East from continued economic growth. Overall, the workshop concluded that bulk transfer along the Phase 2 route would not provide sufficient benefit over a 25-year time horizon to recommend it for further assessment.

The potential for intra-regional water transfer, i.e. to explore the use of stretches of the HS2 route to provide greater connectivity between water supply zones was however considered worthy of further consideration. The workshop participants based this assessment on the assumption that there are likely to be points along the proposed HS2 Phase 2 route between which water resources could be beneficially transported. For example, there is a tendency for a water company's infrastructure to be less developed at the extremities of its operational area. Hence there is a potential benefit in either transferring water between neighbouring water resource supply zones including those of another water undertaker, or providing a cost effective means of enhancing the capacity or resilience of water company's supply network at its periphery. There may also be locations along the route where transfer pipework could help balance local abstraction regimes by moving water from an oversupplied area of one region to an undersupplied area of another. In all these examples, it is possible that water transfer pipelines will be more efficient than local pumping and abstraction. In addition, the technology is well known, and the smaller bore pipework (compared to that required for bulk supply) means a lower impact to HS2 in the event of a burst water main.

It was also noted in the workshop that there may be locations along the route where the embankments could be designed to provide an auxiliary flood defence function, such as the short-term impounding of flood waters during peaks in flood events. Such actions would impact on catchment flood regimes, and this would need to be modelled and risks assessed. However it is technologically achievable, and although it would increase the project costs, these could potentially be met though shared financial models with DEFRA and the Environment Agency. By reducing risk it could help address insurance costs for those living on flood plains, as well as reducing the social and economic costs of flooding.

Finally, the risks from interactions between the water sector and the HS2 Phase 2 project were identified by workshop participants. Principally these relate to changes in catchment flood regimes due to embankments and other HS2 structures built along the route. The expectation however was that mitigations would be included in the HS2 Phase 2 design.

	1	2	3	4	5
A	Climate Change	Increased rainfall and flood risk	-	-	Increased flood risk (impacts on the track)
B	-	Flood Protection	-	-	Increased risk to HS2 if used as flood protection
C	-	-	Intra-Region Transfer	-	Increased risk to HS2 from burst mains if used as route for intra-regional water transfer
D	-	-	-	Bulk Transfer	Increased risk to HS2 from burst mains if used for bulk water transfer
E	-	HS2 alters flood regime and increases flood risk	-	-	HS2 Phase 2 Rail Line & Route

Figure 7 HS2–Water Sector Risks

3.1.4 HS2-Transport Sector Beneficial Interdependencies

Workshop participants identified that the proposed HS2 Phase 2 route will potentially release road capacity as well as freeing up capacity on the conventional rail network as it encourages passengers onto the HS rail network. The release of trunk road and conventional rail capacity would be beneficial in permitting more freight to be transported via these existing transport networks. The degree to which these beneficial interdependencies can be realised will depend in turn on HS ticket pricing, and any overall additional stimulus in economic activity and associated future demand for travel and passenger numbers. Other beneficial interdependencies identified by the workshop included the potential for competition between HS2 and air travel and other Train Operating Companies and associated downward pressure on ticket prices.

An opportunity to implement a ticketing system that is integrated with other modes of transport (such as air-travel and HS1) was identified, particularly as the route will potentially open up access to several airports. This was seen as an opportunity to integrate public modes of transport and deliver time efficient travel.

Interdependency was identified between HS2 Phase 2 – as a transformative mega-transport project – and land use planning and policies along the chosen route. This included the need to change and shape local land use plans and policies so as to maximise beneficial socio-economic impacts. However, it was also recognised that there is a possibility of improved transport connections between the South East, the Midlands, Leeds and Manchester having, in time, a negative impact on the economy of other areas such as the South West, East Anglia and Wales.

	1	2	3	4	5	6	7
A	**Economic Growth**	Increased passenger and freight demand; Amending planning policy to shape development opportunity	-	Changing international passenger and freight transport volumes	Changing passenger demand patterns; Need for appropriate policy tools	-	-
B	-	**Roads (International, National and Local)**	-	-	-	-	-
C	-		**Water and Ports**	-	-	-	-
D	-	-	-	**Air**	Development of through ticketing for public transport integration	-	Development of through ticketing for public transport integration Competition between HS2 and air travel
E	-	-	-	Development of through ticketing for public transport integration	**Rail**	-	Competition between conventional TOCs and HS2
F	-	-	-	-	-	**Land Use**	-
G	Wider economic impacts of economic development; Relative economic decline outside HS2 corridor	Frees capacity on road network Opportunities to develop freight lanes on SRN	Shared flood defences	Development of through ticketing for public transport integration; Competition between HS2 and air travel	Frees capacity for rail-based freight	Efficient land use and minimised loss of visual amenity with shared corridor	**HS2 Phase 2 Rail Line & Route**

Figure 8 HS2–Transport Sector Opportunities and Risks

Experience of the construction of the UK's Strategic Road Network, including motorways, led to general discussion of the ability of other utilities and services to make use of HS2's transport corridor cuttings and embankments. HS1 required a significant land-take, but due to legal, political and physical constraints, it has remained difficult to gain access to the land along the route to install additional infrastructure assets or services. The workshop recommended that when defining the legal provisions for the HS2 Phase 2 route, it would be important and beneficial not to foreclose the opportunities of additional land uses, and furthermore, that developers should consider the costs and benefits of providing underground and ‘over-ground’ conduits or other forms of passive provision for future infrastructure. Where additional clearance is necessary to facilitate the passive provision, e.g. through cuttings, across bridges and through tunnels, the associated land-take may make the provision of extra land or physical assets relatively inexpensive The key principle being advocated was planning and designing with an ‘open systems’ approach and provisioning (not foreclosing) future ‘opportunity benefits’.

3.1.5 Other Considerations

Many problematic discussions at the workshop arose whilst trying to identify and evaluate in numerical terms the potential benefits and costs of interdependencies of thirty years hence, where these were typically characterised by uncertainty in the future demands on infrastructure. This included assessing whether technologies may change so radically as to make provisioning, such as setting aside additional land or building additional capacity, in the end unnecessary. This case study and the workshop discussion therefore highlighted the need for a process for calculating the value of future ‘opportunity benefits’, i.e. what future benefit stream might be derived from a policy of passively provisioning when there is uncertainty in the future level of need for such infrastructure capacity.

A lack of structure for local engagement was identified as a potential challenge to considering the wider benefits of interdependencies at the local and regional scale. In combination with this, there is value in moving beyond the conceptualisation of HS2 as being just a public transport railway, and instead viewing it as a tool for regeneration, i.e. as an ‘agent for change’.

The workshop concluded that any learning from this discussion and subsequent related work on interdependencies should be carried forward to Phase 3 of HS2 should it go ahead. Even if options are dismissed at this stage, the geography, environment demographics, demand patterns and route may make them attractive in the future. For example, should the route pass through Areas of Outstanding Natural Beauty, such as large National Parks, it may provide an opportunity to route existing *and* additional cables via an HS2 infrastructure corridor so as to minimise additional adverse visual and environmental impact and offset pre-existing adverse visual and environmental impacts .

4 Evaluation of Workshop Results

This section provides the results of a desktop review to assess the success of the workshop at identifying, creating and assessing potential interdependencies. These are then compared systematically against the existing literature to judge whether the workshop revealed or created any new forms of interdependency not previously considered, as well as the success in identifying previously reported interdependencies. In doing so, additional evidence has been gathered to support the evaluation of the combined set of interdependencies from all sources.

The following tables (Table 1 to Table 4) reproduce the interdependencies identified through application of the IPMF. The referencing in brackets refers to the grid reference in the relevant matrix mapping figure. For example (A6) in Table 1 below relates to the box A6 in Figure 4. The following observations are made in respect of the findings:

1) It has not been possible to complete an exhaustive comparison of the interdependencies identified in the workshop against all interdependencies previously reported in the literature.
2) Although some interdependencies identified in the workshop were not found in the set of literature reviewed for this study, this does not comprise proof that they have been universally disregarded or overlooked by all previous studies.
3) The absence of any additional references or evidence to support an interdependency identified at the workshop cannot be taken to imply that a given interdependency is impracticable or undesirable.
4) Where shown to be feasible and desirable, the discovery or creation of 'novel' interdependencies provides evidence of the potential utility of the IPMF.
5) While there is evidence that the consideration of the general concepts of interdependency between the energy infrastructure and the rail network have been advocated elsewhere, it should be noted that, as with many of the other interdependencies, there is no evidence they have actually been considered for HS2 Phase 2. For example, the use of railway embankments as flood defences have been suggested in generic terms, but they have not been explicitly suggested or considered in relation to High Speed 2 Phase 2 prior to this workshop.

In addition to the interdependencies listed in Section 3, the workshop stimulated some peripheral discussions into the potential for integrating more novel energy harvesting technologies. For example, trains are already planned to be built with regenerative breaking, and a tunnelled stretch of the high speed rail line between Paris and Amsterdam is covered with solar panel as is Blackfriars Railway Bridge in London [21].

While there may not have been a large number of novel interdependencies identified through the application of the framework, the benefit of bringing these together in a systematic and structured way should not be dismissed. The structure also allows for more complex networks of interdependencies to be identified. These higher-order interdependencies might give rise to emergent benefits (for example through feedback loops) that are not always clear from a single interdependency. In each of these cases the framework adds a means to holistically assess and value these interdependencies once they have been identified.

Table 1 Wider evidence of the consideration of ICT Interdependencies

<table>
<tr><th>Interdependency</th><th>Evidence from elsewhere</th></tr>
<tr><td>Between HS2 and Core Comms networks which provide resilience for HS2 control systems (A6)</td><td>Unclear whether existing communications networks have been considered for use in enhancing the resilience of HS2's dedicated control systems.</td></tr>
<tr><td>Between HS2 and Mobile Comms which provide resilience for HS2 systems (D6)</td><td>Unclear whether existing mobile communications networks have been considered for use in enhancing the resilience of HS2's dedicated signalling and communications systems.</td></tr>
<tr><td>Between HS2 and Mobile Comms which provide services to Passengers (D6)</td><td>The importance of providing access to communications networks to facilitate passenger convenience and business productivity have been acknowledged by HS2 Limited [14], though the extent to which access to mobile networks will be considered in detailed relation to the route is unclear.</td></tr>
<tr><td>Between HS2 and Data Centres which provide services for Passenger information (E6)</td><td>While the provision of journey information to passengers is to be expected, there is no known evidence of how this will be achieved for Phase 2 of HS2.</td></tr>
<tr><td>Between Core Comms networks and HS2 which could provide an additional route for cables (F1)</td><td rowspan="3">Report by Frontier Economics [6] explicitly suggests considering the potential of other utilities (naming 'super-fast broadband' providers) of using the rail corridor.
Report by UCL and University of Bristol [22] identifying the benefits and costs of provisioning ducting for dark fibre along Phase 1 of HS2.
Transport networks providing right of way for utilities to lay communication cables also recognised in OECD report [7]</td></tr>
<tr><td>Between Backhaul Network and HS2 which could provide an additional route for cables (F2)</td></tr>
<tr><td>Between Access Network and HS2 which could provide local opportunities to access remote and rural areas. (F3)</td></tr>
<tr><td>Between Access Network and HS2 which could provide road/rail crossing points. (F3)</td><td>None identified.</td></tr>
<tr><td>Between Mobile Networks and HS2 which could provide shared or additional masts (F4)</td><td>A joint venture between Marconi and Network Rail (Ultramast) owned the rights to establish commercial GSM transmitters on railway land but this was subsequently sold.
An upgrade of rail communication systems by Network Rail led the Minister for Culture, Communications and Creative Industries to say in an interview with the FT [23]: "Network Rail is doing a £1bn project to build its own mobile infrastructure for signals. We need to look at opportunities and [see if it can] give an extra string to the bow of those that want to roll out commercial networks."</td></tr>
<tr><td>Between Data Centres and HS2 which could provide potential for new locations resulting from low latency connections along straight route. (F5)</td><td>There is no known consideration of the impacts to latency of running a communication cable along the relatively straight HS2 route. It would be reasonable to assume that HS2 would have a transformative effect in terms of greater economic activity along the corridor, and therefore along with increased travel demand, there would be increased demand for ICT connectivity along this corridor, i.e. a correlated demand.</td></tr>
</table>

Table 2 Wider evidence of the consideration of Energy Sector interdependencies

Sector	Interdependency	Evidence from elsewhere
Energy Sector	Between HS2 and sites for new Nuclear Power Stations which could provide the power for HS2 operation (A5)	• While HS2 may indirectly draw power from Nuclear Power Stations through the National Grid, there is no indication that this would influence or be influenced by the location of the stations.
	Between HS2 and Existing Electricity Networks which could provide power to HS2 (C5)	• This is a necessary interdependency, with feeder stations positioned along the route planned to take power from the National Grid and transform the voltage for use powering the trains
	Between Existing Electricity Network and HS2 which could provide access agreements for Utility Providers (C5)	• Report by Frontier Economics [6] explicitly suggests considering the potential of other utilities (naming 'electricity transmission and distribution') of using the rail corridor.
	Between Electricity Supply around Sheffield and HS2 which could provide the potential to build new generation facilities (E2)	• Report by Frontier Economics [6] explicitly suggests considering the potential of other utilities (naming 'electricity transmission and distribution' providers) of using the rail corridor.

Table 3 Wider evidence of the consideration of Water Sector Interdependencies

Sector	Interdependency	Evidence from elsewhere
Water Sector	Between HS2 and Flood Prevention which affects the resilience of the Railway (B5)	• Generally, the impacts of flood prevention on railways have been widely discussed. This is a necessary interdependency.
	Between Bulk Water Transfer and HS2 which could provide a potential route. (E4)	• Report in Feb/March 2012 noted that United Utilities had considered a £2.6 billion North-South water pipe using the route of HS2 [24]. This is at odds with Water UK which is against such bulk transfer schemes [25].
	Between Intra-Region Transfer and HS2 which could provide a potential route	• The concept of intra-Region (here meaning inter-water authority) transfer has been explored by Water UK. • United Utilities 55km, £125m bi-directional pipeline between Manchester and Liverpool (West East Link Main) is an example of recent physical transfer infrastructure [3].
	Between Flood Protection and HS2 which could provide opportunity for excess water detention and storage using embankments (E2)	• A report by Engineering the Future [4] suggests the potential for the use of railway embankments as flood defences. • Report for DEFRA/EA [5] suggesting existing rail embankments may not be fit for flood defences. Notes that in some circumstances they may provide partial barriers.
	Between Flood Protection and HS2 which could alter the geography of flood plains (E2)	• The impact of the route on flood plains was investigated in the Appraisal of Sustainability for Phase 1 [26], so it is likely that this will be considered for Phase 2.
	Between HS2 and Climate Change which could increase risk of flood damage to track (A5)	• The impact of climate change on flooding was investigated in the Appraisal of Sustainability for Phase 1 [26], so it is likely that this will be considered for Phase 2.

Table 4 Wider evidence for the consideration of Transport Sector interdependencies

Sector	Interdependency	Evidence from elsewhere
Transport	Between Rail and Economic Growth which could affect demand patterns (A5)	• It is essentially an underlying hypothesis of the project that HS2 will improve economic growth, but this point considers the impact on a changing economy on the demand for rail travel. • There is some evidence of this associated with High Speed 1 and other High Speed railways around the world. • The impact of different economic scenarios on demand for travel are considered as reported in The Economic Case for HS2.[27] • The impacts of HS2 on regional development have also been studied by academics at The Bartlett School, UCL.[28] • Proposals suggest that high speed rail is of greatest benefit to larger towns it links This has been seen in Japan (with Tokyo and Osaka) and Spain (with Madrid and Seville), while in France more organisations have moved their headquarters to Paris with less need for visitors to stay overnight [29].
	Between Roads and HS2 which could be integrated with 'through ticketing' (B7)	• Such mixed mode public transport through ticketing is established in Greater London with the Oyster Card and similar national schemes have been proposed [30].
	Between Road Networks and HS2 which could provide additional road capacity through modal shift in transport (G2)	• The impacts on road use are discussed in the Economic Case for HS2 [15] and elsewhere.
	Between Economic Growth and HS2 which could cause a decline in economy outside of North/South corridor (e.g. Wales and West Country) (G1)	• There are reports on the agglomeration and labour market pooling effects of high speed rail produced to support the business case, but these do not mention how such agglomeration could affect other regions. • Studies of existing high speed rail routes suggest they reinforce existing regional economic trends and can have detrimental effects on the economies of regions that become perceptually further away [29].

5 Conclusion

1. Adopting a holistic, 'open systems' approach to the planning and design of large scale infrastructure opens up the possibility of anticipating and either accommodating or benefitting from the interactions arising across the whole network of infrastructure systems. Interdependency planning and management provides an approach which facilitates the identification and purposeful design of beneficial engineering synergies, which could result from co-location, aggregation effects or more specific integration with other interacting infrastructure systems.

2. A developmental version of the Interdependency Planning and Management Framework (IPMF) has been applied at a workshop to identify potential engineering interdependencies between the High Speed 2, Phase 2 route rail infrastructure and four other engineering sectors: water, ICT, energy and transport.

3. The principal focus for the workshop was to identify a set of interdependencies with the potential to enhance the value of the HS2 Phase 2 project. Although presenting significant engineering and project delivery challenges, the following interdependencies were considered to be of sufficient interest to merit further investigation:
   1) Using the High Speed 2 Phase Two corridor to provide additional electricity distribution capacity into Sheffield and Manchester;
   2) Using the High Speed 2 Phase Two corridor to provide the capability for intra- regional water transfer;
   3) Using the High Speed 2 Phase Two corridor (and associated construction) to provide the capability for additional flood protection adjacent to the route;
   4) Using the High Speed 2 Phase Two corridor to provide additional capacity for the distribution of ICT infrastructure (e.g. fibre optic cables).

   Other beneficial and adverse interdependencies were identified and are reported in the main report.

4. The examples of interdependency identified in the workshop for the HS2 project were dependent principally on viewing a new railway route as a shared infrastructure corridor. The benefits identified included: potential savings in legal and construction costs, as well as aesthetic and environmental benefits from not impacting adversely on other parts of the natural environment. In the case of flooding, the interdependencies identified comprised the possibility of the HS2 embankments increasing flood protection by default, intentionally designing embankments to enhance flood protection, or conversely HS2 construction creating an adverse increase in flood risk and thereby requiring the design of mitigation measures.

5. The implementation of the matrix mapping tool within the IPMF can be characterised as a holistic, 'open systems' approach, since the matrices used to model the principal infrastructure system elements (assets and policies) were not unduly constrained: they were extended to accommodate the wider cross-sector 'system of systems' spanning a range of utility sectors and policies likely to have the potential for significant interaction.

6. Creativity was encouraged through the shared cross-sector, participation in the interdependency identification and assessment process. The matrix-based layout promoted a structured and systematic search for interdependencies and provided the means for capturing the conceptual modelling of infrastructure dependencies and interdependencies developed during the workshop.

7. The IPMF provided a structured means to bring together a broad range of stakeholders drawn from four different infrastructure sectors: Energy, ICT, Water and Transport, with interests and knowledge spanning policy, engineering design and infrastructure operation. However there is the potential for biases to feed through into the workshop results according to the beliefs and domain knowledge of the individual participants. Established approaches exist to minimise such workshop biases, and these should be used along with a mixed mode of research, e.g. complementary desktop studies, interviews and stakeholder surveys, to ensure robustness of outcomes.

8. The workshop identified the importance of defining with sufficient clarity the core purposes of the interacting set of infrastructure systems under investigation. Firstly sufficient clarity in purpose of the proposed infrastructure under development is necessary to permit the identification, planning and design of infrastructure interdependencies; in this case study, where these will assist in the integration of a mega transport infrastructure project within existing local and regional transport networks. For example, the published purpose of the HS2 infrastructure is to increase rail commuting capacity in and out of London, to alleviate overcrowding on other major rail routes such as the West Coast Mainline (WCML), and in to do this in a way that reduces commuting times between major UK urban populations in the North of England, the Midlands and South East of England and London. Secondly, without establishing the impelling purpose(s) for each interacting system, and then the relative importance amongst stakeholders of fulfilling each assigned purpose, it is difficult or impossible to investigate the potential for emergent *beneficial interdependencies* and the degree of investment merited in purposefully engineering these as additional outcomes.

9. The economic appraisal of engineered interdependencies similarly requires a clear understanding of the core needs that any interacting infrastructure systems are expected to meet and associated measures of operational performance, such that appropriate value may be attributed to the goods and services they provide to society. Without this, identifying and evaluating the beneficial and adverse impacts from proposed engineered interdependencies becomes problematic, and auxiliary infrastructure could compromise the core infrastructure design goals.

10. The desirability of fulfilling purposes which are auxiliary to the core infrastructure development being planned will depend on the overall assessment of the additional economic, environmental and social benefits of such a combination. In the example of an HS2 rail service with trackside water transfer pipelines, account would need to be taken of any risk of disruption should the water main burst and any such possibility would have to be sufficiently low before it could be considered acceptable to rail operators and users. In addition, the workshop highlighted some of the practical difficulties of engineering a shared infrastructure corridor, including: 1) Organisational: establishing the need to create or manage an interdependency and instituting the collaborations needed to share risks

and/or opportunities 2) Financial: the willingness of investors to pay for interdependent benefits; 3) Timing: synchronising interdependent infrastructure investment; 4) Delivery: managing more complex or complicated infrastructure projects in accordance with planned schedules.

11. For large and transformative infrastructure developments, additional higher-level purposes can become ascribed to the core development as it co-evolves with, and is integrated as part of, the wider network of infrastructure and socio-economic systems. Within current engineering design and planning processes there is a tendency for such needs to emerge during the evolution of the project or post-project. For HS2, the examples of generating economic development around the mainline stations, redistribution of economic growth, and contributing to a net increase in economic output were all identified and discussed in the workshop, but are arguably extensions of the initial specific goals for HS2 Phase 2 that have been identified relatively recently. Given the high costs of design changes to large-scale infrastructure, and post-consultation the near impossibility of changing fundamental design features, there is a clear financial benefit in being able to assess wider socio-economic needs and create beneficial interdependencies early on in the project life-cycle.

12. It is therefore important for engineers and planners to have methodologies capable of: 1) identifying and designing the core infrastructure to meet higher-level needs, i.e. even where these are exogenous to the infrastructure being developed; 2) assessing whether a network of infrastructure systems, taken as a whole, comprises all sufficient and necessary capabilities to meet those desired higher-level, exogenous needs and can be configured such that it provides the additional cumulative benefits of a desirable interdependency; and 3) identifying *dependencies* that the core infrastructure development project has on 'auxiliary' supporting infrastructure (legacy and future), i.e. identifying where these are essential to operation of the core infrastructure, and where poorly performing auxiliary infrastructure of would undermine the successful project implementation.

13. The HS2 case study provides examples in which it would be feasible to plan for future beneficial interdependencies (opportunities). This could by provisioning for future incremental development, sometimes referred to as 'passive provisioning' and retaining flexibility, and not foreclose for future opportunities the principle of designing for beneficial interdependency at the level of the whole infrastructure network, is the principle of planning and designing for adaptability and to maximise value in the 'emergent order' with uncertain and changing socio-economic needs. Both these principles could become an important strategic consideration in the planning, design and delivery of large-scale infrastructure such as HS2 Phase 2, and one which requires trade-offs, balanced judgements regarding uncertain costs and benefits at national and supra-national level of infrastructure.

14. In such highly networked and interacting environments, it is no longer possible to view mega infrastructure development as individual, divisible projects, with separate Benefit-Cost Ratios to support discrete investment decisions, i.e. there is also a need to be able to establish the potential aggregated benefit derived from linking the investment and appraisal of multiple infrastructure investments including any phasing of these. For example, if the auxiliary purpose for a new mega transport project is to facilitate economic growth and regeneration, then issues such as the sufficiency of accessible airport capacity; supportive changes in local and regional economic development plans and policies;

planning to increase utility services in the expected economic growth areas including greater ICT connectivity, may all be necessary for the successful delivery of the desired regeneration.

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