SMART INFRASTRUCTURE: BENEFITS AND PITFALLS

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SMART Infrastructure: Benefits and Pitfalls

Introduction

The purpose of this White Paper is to provide a definition for smart infrastructure and highlight some of the key challenges faced in the development and sustenance of smart infrastructure. While we choose to focus on four areas of interest that are important to improving the understanding of wide range of stakeholders why 'smartness' is important, we believe these raise issues that are common across other domains where smart infrastructure has a purpose, such as Smart Cities (ref…) Smart Nation (ref…) and Smart Communities (ref…). These areas are are: (i) Smart Information Systems and their deployment: a discussion of the business case for smartness and incentive issues (ii) Transportation: as a specific problem domain, transportation raises issues that are common to systems involving interdependencies between users and infrastructure spread across networks (iii) Socio-technical systems dynamics: systems that employ smarts and their evolution as users adapt to the smartness in the system (iv) Sensors: the technology, our reliance on it, and the resilience built into them. By discussing each of these areas, we provide policy makers, academics, and industry experts with broad understandings of the issues of concern that are not limited to their specific area of interest and hence initiate a healthy debate on the solutions that will encompass both human and engineering challenges involved.

The rest of this paper is structured as follows. We first describe smart infrastructure and then move on to explain the multiple benefits of such infrastructure. We then proceed with a deep-dive into each of the above-mentioned four case studies. Finally, we conclude with a discussion and extract key conclusions from our analysis of the broad areas of interest.

What is Smart Infrastructure?

> *'Smart infrastructure'responds intelligently to changes in its environment, including user demands and other infrastructure, to achieve an improved performance.'* [RAEng, 2011]

A smart system uses a feedback loop of data, which provides evidence for informed decision-making. The system can monitor, measure, analyse, communicate and act, based on information captured from sensors. Different levels of smart systems exist. A system may:

- collect usage and performance data to help future designers to produce the next, more efficient version;
- collect data, process them and present information to help a human operator to take decisions (for example, traffic systems that detect congestion and inform drivers);
- use collected data to take action without human intervention

These definitions and observations are data and engineering dominated and are from a workshop held in 2011. It is already apparent that the concept of SMART is very dynamic and hence it is to be expected that SMART will encompass a wider set of disciplinary views in the future

Why use SMART Infrastructure?

The state of a set of assets that make up an infrastructure system will determine what quality the service that is derived from that system will have. The term SMART is topically being used in two ways, one to describe the process of assessing the state of the assets by the use of sets of data and two to describe the nature of the decisions that are made with regard to how to manage those assets. The purpose of using data is to provide better assessments and hence better quality services. The hypothesis is that better data delivers better decisions throughout the lifecycle of the assets, ranging from data about design through data concerned with implementation to operational data. The validity of this hypothesis is reinforced by case studies for example in the aerospace industry, the automotive industry and in ICT. where cradle to cradle exploitation of data delivers better services and lower cost and with greater resilience to unexpected events; examples include realtime jet engine health on civil aircraft, in car maintenance assessment and storage systems diagnostics and self checking in large data centres. The extension of these principles to other engineered components and assets within other infrastructure sectors is in progress, such as BIM, and IVHM in the rail industry.

The nature of the decision making processes that are instantiated to use the data are less well developed and are quite often commercially sensitive, since they provide commercial advantage to the service provider. (Ref to RAEng report on connectedness) The context in which the data are used tends to be single sector, so that the services that are derived from a number of infrastructure sectors are also less well developed. The open data initiatives are of course aimed at at least ensuring data interoperability between sectors, but multi-sectoral decision support tools are less well developed, and without such tools the real potential of SMART-ness will not be realised.

Modelling scenarios where the infrastructure systems that are interdependent provide high value services would be a good place to start a process of understanding how to develop the tools that are needed. An example might be the provision of electric charging points for electric vehicles, where the supply (derived from central base load and local intermittent renewables) has to delivered at the *places* where the demand is (both using roadside charging and in road charging) and ensuring the *capacity* is sufficient given other neighbourhood demands for electricity. Another example could be flood management in urban areas during heavy rain that dynamically adjusts water flows in drainage ducts according to where the rain falls, data on flood risks to buildings and roads and other non-water system assets, and data on the state of the overall catchment areas capacity to handle greater volumes.

Without such analysis a patchwork quilt of non-interoperable decision support systems will grow and the realisation of holistic SMART analytics will not be realised.

This analysis suggest a number of open questions that will need solutions and answers before large scale implementation of smart infrastructure should be attempted;

- How to ensure the integrity of the analytics
- Development of open and common metadata structures
- Provenance of data sets, particularly for real time systems
- Representation and visualisation standards.

Smart Information Systems and their Deployment

As our ability to pack exponentially more powerful computing capability onto smaller devices, a new generation of information services is coming about. Increasingly, multi-sensor systems, plugged into the infrastructure around us and carried with us in our pockets, gather data securely and provide us with real-time information about the state of transportation networks, power grids, and even the human body. Coupled with powerful, scalable, cloud computing capability, system mangers can be provided with real-time analytics on the performance of their system, helping them to trace faults, identify opportunities to improve services, and share information with other infrastructure providers as part of an orchestration of smart, interdependent infrastructures.

Such smart systems come with significant benefits including speed, efficiency, and resilience. However, the business case for such smarts may not always stack up due to high capital costs, market forces, and ethical and privacy concerns. To provide a clear example of such potential obstacles to the creation of smart infrastructure, we focus on the case of the nationwide roll-out of smart meters to 26M homes by 2020 as mandated by the government [ref-smart-meter-2020].

The ongoing deployment of (electricity) smart meters in the UK is a highly complex infrastructure project at all levels, whether technical, commercial, or ethical. We elaborate on each of these aspects in what follows and the kinds of solutions that have been proposed. While we focus on electricity, we believe some of the issues raised would apply to other utilities (water, gas, waste).

At the technical level, data needs to be collected, transmitted, and stored in ways that will accrue benefits for infrastructure providers and government agencies while also ensuring that people’s privacy concerns are allayed. According to government policy, smart meters will collect and transmit data to the Smart DCC (Data Communications Company) at half-hourly intervals. The half-hourly periodicity of data collection is meant to mirror the timescale over which energy trades are settled on the wholesale market. Within the home, data may be collected at higher frequency and transmitted (over RF) to an in-home-display for users to have better visibility of the consumption of specific devices [ref-smets-2].

Against this background, recent research in smart energy systems has focused on how to make best use of such data to help consumers and utilities save energy, reducing bills and peaks on the grid [agent-dsm,figure-energy,chariot-paper,agentswitch]. For example, it has been suggested that such data could help users understand how appliances consume energy over time (as opposed to instantaneously), and automated tools could be provided to them to help them, choose the best energy contract, adjust their consumption (reduce or shift appliance usage) to times that would be most beneficial to themselves and the electricity grid. However, such services either require that each appliance in the home be individually monitored or that aggregate metering data be collected at higher frequency (every 10s) so that appliance usage may be disaggregated from the aggregate feed using AI techniques [ref-nilm]. While the former comes with a high capital cost, the latter requires changes (potentially a software switch) to the physical make-up of smart meters (which would also incur a high cost) and the protocol regimenting data transmission. However, collecting data at higher granularity also raises data storage problems (at least 260,000 data points per home over a month) and privacy concerns as the data may reveal highly personal activities and interests that could be exploited for criminal activity. Given the high levels of incentives involved in gathering data about user activities, devices have been developed that can potentially collect data within the home (via or acting as an IHD) and transmit it to third parties, thus bypassing the security protocols in place to avoid unwarranted use of personal activity data. Given the costs of policing this, in future, it is therefore unlikely that it will be possible to stop consumers from accessing and providing this data to anyone they wish (similar to the advent of the mp3 format in the 90's).

Now, the current policy around the roll-out of smart meters [ref-roll-out], requires commercial organisations (i.e., energy utilities) to pay for the installation of meters, while the data is transmitted to the SmartDCC, from which, in turn, utilities would have to purchase **(?)** a licence to retrieve their consumers' data. While this makes technical sense, allowing the Smart DCC to rapidly shift customers between suppliers, it makes it harder for utilities to develop a business case for the installation of smart meters in the first place given the costs of installation and faster churning of customers (resulting in higher marketing costs potentially). Furthermore, it is, as yet, unclear how and, through what commercial arrangements, the SmartDCC and utilities would share their energy usage data with other infrastructure providers to provide enhanced services to consumers and achieve further efficiencies (e.g., predicting traffic conditions given estimates of home or commercial energy use or shifting water pump usage given expected peaks on the electricity grid).

It is no surprise, therefore, that the protocol for data sharing in the smart meter deployment has faced several delays, causing significant difficulties for smart metering manufacturers as they try to keep up with regulations and while future-proofing their products so that they may support more advanced services that would come about further down the line [agentswitch, chariot-paper, smarthermo]. This highlights the need to carefully craft the business model around the deployment of smart infrastructure where the cost of installation and ownership of infrastructure is shared across multiple and self-interested actors. Business models that work for both private and public bodies also become very complex when such bodies have to define infrastructure policy while coping with market forces that rely on a sustainable energy supply. Long-term visions become harder to realise when short-term business gains are the focus of actors in the system. Moreover, such visions have to be robust against external factors such as the integration of intermittent renewable energy supplies, energy supply from other countries (that are beyond National Grid's control), and disruptive technologies (e.g., Electric Vehicles) that impose even higher demands on the grid.

Technical	Data collection, storage, and communications have to align to the needs of multiple stakeholders within the specific sector and operators of other infrastructures in order to achieve the desired benefits.
Ethical	Personal data collected by smart infrastructures may lead to loss of privacy.
Governance	The orchestration of services that cut across multiple interdependent infrastructures,potentially owned by different self-interested actors will require the design of appropriate incentives to allow for viable business models that help achieve the overarching goals of the system.

Table 1: Challenges for interdependent smart infrastructures.

Smart Transportation Networks

Smarter transport systems are encouraging cities to enhance mobility, reduce emissions and personalise user experience. It is estimated that from 2012 to 2020 $100bn will be invested worldwide on smart city infrastructures, and $22.4bn of that will go into smart transport. Smart transport systems do not just involve networks installed by operators but also a raft of new bottom-up initiatives such as real-time taxi and ridesharing apps as well as smart sat nav systems powered by people (e.g., Waze). It is expected that there will be 50 billion moving smart devices in circulation around the globe by 2020, with about 5% of them in vehicles.[1] Such smart transportation systems thus freeride existing IT and communication infrastructures, and exploit increasing interconnectedness and openness.

While collecting data from across large numbers of spatially distributed (increasingly autonomous) actors and infrastructure, smart transportation networks also self-organise by virtue of the individual decisions taken by such actors. While these smart devices will keep individual users and their vehicles better informed about the state of the network and help them route around it in across multiple modes of transport, these smart devices may act as sensors of the smart system to collect real-time traffic information and to monitor people's travel patterns. As it is expected that there will be 50 billion moving smart devices in circulation around the globe by 2020, with

[1] https://www.itso.org.uk/wp-content/uploads/2012/05/Smartsolutions_Guardian_3apr14.pdf

about 5% of them in vehicles,[2] we can expect such smart networks to grow in capability and personalization over the forthcoming years.

In contrast, however, to smart information systems underpinning grids and water networks, the transport sector involves many more actors (drivers, trains, cars, passengers) all connected in much more complex ways. With this complexity comes many opportunities for innovative services and business models. In what follows, we highlight two key areas of growth in the transportation sector and discuss some of the challenges faced in achieving the benefits they promise to bring about.

Connected Autonomous Vehicles (CAVs)

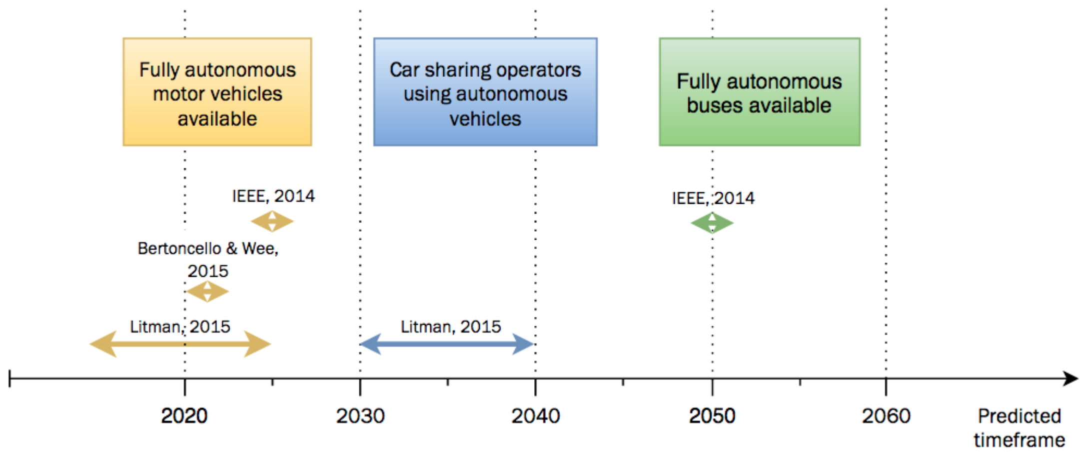
The advent of autonomous vehicles is likely to be a significant game changer in the landscape of transportation systems. The Tesla Model S and Google Cars for example can self-drive to different degrees and are increasingly gaining popularity. While reducing the workload for drivers, they also offer the opportunity to manage traffic in better ways. For example, by getting cars to communicate with each other and coordinate into fleets, it may be possible to reduce delays and congestion significantly.[3] Moreover, by virtue of the sensors in and around such cars, valuable traffic and environmental data can be collected to measure road conditions, usage, and traffic (from non-autonomous cars). However, this vision of "connected" autonomous

[2] https://www.itso.org.uk/wp-content/uploads/2012/05/Smartsolutions_Guardian_3apr14.pdf

[3] A 50% fleet transition to CAVs could generate a 22% improvement in effective lane capacity; increasing to an 80% capacity improvement with a fully autonomous vehicle fleet.

vehicles that can adapt to traffic, weather, and user demand is challenged by the disparate systems that regiment established infrastructure. For fleets of autonomous cars to coordinate, they will need to work in lock-step with traffic information systems that will inform them of lane closures, bottlenecks, accidents, and other events in real-time. In turn, traffic managers will require access to potentially sensitive information about users' destinations and time constraints in order to effectively manage congestion. They may also choose to employ novel road pricing strategies and prioritization to maximize the effectiveness of connected autonomous vehicles. Crucially, new regulations will need to be considered to clarify civil and criminal liabilities in relation to autonomous cars. For example, who should be held responsible should an autonomous car take a wrong turn and causes an accident? Given the interdependencies that will be introduced by smart systems trying to optimize routes for individual users, traffic for a given city, and even CO_2 emissions., it will become increasingly unclear where the responsibility lies. Hence, the legal ramifications of such systems are essential to ensure their wider acceptability and success.

Figure 1: Predicted Timeframes of Technology Transitions (from Bentley et al., XXX?)



[To discuss:

Risks around the resilience of CAV fleets providing urban transport services (in place of private 2]

Shared Transport:

Studies have showed that, in some cities, it is possible to take everyone to their destination at the time that they want with 20% of the cars. [4] This is only achievable if we are incentivized to share rides, car parks (i.e., in schemes where one's driveway can be used by someone else) and car ownership (whereby someone can book one's car for a short trip at a cost). This requires smarter transportation and communication infrastructures to make the sharing economy safer, more efficient and more sustainable. The UK government is removing barriers that stop people sharing their assets, and will empower people to make more from their assets and skills. [5] However, more needs to be done to ensure that users and owners are incentivized to collaborate to use existing resources more efficiently. While some of the answers lie in road pricing and regulation, more needs to be done to change mindsets and to equip users and owners with better information systems to guide their choices. Crucially, for actors in the network to share resources, some level of trust needs to be established between them. This may take the form of bottom-up approaches such as ratings systems (e.g., for drivers and riders in ridesharing schemes) and social-networks-

[4] [http://www.ft.com/cms/s/0/24f6aec4-6688-11e5-97d0-1456a776a4f5.html#ixzz3neWHHkab].

[5] To demonstrate the benefits of the sharing economy, the government will launch two pilots in the Leeds City Region and Greater Manchester in 2015-16 to trial local sharing initiatives in the areas of shared transport, shared public space and health and social care [https://www.gov.uk/government/publications/sharing-economy-government-response-to-the-independent-review].

based metrics (e.g., friends of friends) or more top-down approaches such as licenses to drive others (i.e., sames as a taxi) or to allow others to park on one’s driveway.

While we have focused on road-related challenges, it is clear that these are but some of the issues that will be faced as we try to evolve smarter transportation systems. Other major challenges will also arise with the electrification of transport (as discussed earlier), the advent of high-speed rail links between different parts of the UK, and the use of more intelligent navigation systems. Table X summarises some of the challegnes we foresee in this sector.

Technical	The design of autonomous cars and traffic information systems that use the information they provide will need to be coordinated.
Social	Users of shared infrastructure will need to be incentivized to participate in such schemes in the long term. Trust mechanisms will need to be developed to ensure they are comfortable with shared ownership and use.
Governance	Behavioural, regulatory, and economic changes over time have direct consequences for the operation of smart transportation systems. Structures will need to be more adaptive over time.

Table 2: Challenges for interdependent smart infrastructures.

Socio-Technical/Political-Economic Systems Dynamics

Contact: John Beckford (for input)

The rate of change processes enabled by information systems is such that other processes (organisational change, education, legal constructs, accounting mechanisms) are stressed and maybe prove unfit for purpose. As the exploitation of data sources, high speed ubiquitous networks and fast analytics becomes pervasive, these stresses and possible fractures in processes could cause at least expected efficiency gains not to be realised and at worst major failure of business processes or social interactions. The potential transformation of financial markets by developments such as blockchain-enabled trading and cryptocurrency also produce disruptive and profound effects.

The planning horizon for business process change is often modelled on annual accounting practices, quarterly returns and supply chain dynamics. If ICT enabled business process transformation continues to accelerate as it is now, these planning processes will prove unfit for purpose in the near future, and businesses and services will suffer. For infrastructure specifically this could cause disruption in the processes that control systems where supply and demand dynamics are coupled to price of subsidiary services (e.g. spot buying of electricity generation, dynamic road user charging, air ticket prices based on demand and capacity). Whilst these factors may be of value to businesses and achieving demand side efficiency gains it will also be necessary to understand how acceptable they are to the end user of the services, the general public. Early experiences with simple smart electricity metering shows the unpredictability of impact of smart technology on social and individual behavior.

The information that is derived from the Smart ICT infrastructure attached to all other infrastructure systems enables decisions to be made more quickly and on the basis of better quality data. But the quality of those decisions will also be significantly affected by the analytic environment which is used to produce decision options. If that environment is too prescriptive (rule based) the dynamics of the situation may not be captured, if it is too flexible too many options may be produced and uncertainties may become unacceptable resulting in indecision. If SMART is to live up to expectations, the design and governance of the analytic frameworks and system dynamics may be the most critical factor to be concerned about in SMART infrastructure once the data sources and ICT infrastructure are in place.

Without coherent governance of the services derived from smart infrastructure system of systems, the benefits will almost certainly be less than might be possible. The system of systems is made up of not only the end to end design and engineering of the technical solutions but also the management and financing of the services and related infrastructure throughout their lifetime, including their maintenance and upgrading. What must also be taken into account is that infrastructure systems are interdependent so changes to one may have a significant effect on the performance of services derived from another. An example ids where a cost cutting measure imposed on networks used to control electrical distribution centres, which had been using dedicated data communication lines with very predictable performance parameters was replaced with the internet, where such parameters were not predictable. This resulted in service breakdowns and systems damage. The example is one where the financial system and the engineering system were interdependent in a way that had not been understood at the requisite level of detail, and changes to one had serious negative effects on the other.

Sensing Systems

Smart infrastructure typically implies smart sensing systems deployed to monitor equipment and general infrastructure (e.g., HVACs, transportation networks, cars, energy systems etc..). One of the main goals of such sensing systems is to ensure that the infrastructure is operated within its safety bounds and maintains its efficiency levels. This is typically achived by collecting data on various timescales (seconds in the case of energy monitoring for example or months in the case of concrete structures) .[6]

As the cost of sensing technology has come down, infrastructure is being increasingly monitored by arrays of low-cost sensors deployed to form sensor networks that can gather data and communicate such data over multiple hops to a gateway that sends data over to cloud-based analytics engines. Such networks have been increasingly deployed for condition monitoring in critical infrastructures, especially ageing infrastructures such as old bridges and old tunnels. Some sections of the London Underground, for example, are over 100 years old and the buildings on the surface above, as well as other underground structures around these tunnels, have changed drastically in that time. The cost associated with replacing any section of the Underground network both in terms of capital investment and associated user delays would be tremendous. Henc, sensor-based monitoring is used to get a better

[6] https://infrasense.net/pub/WSN_ICE.pdf.

understanding of the problem, allowing for a more cost effective solution, and to monitor the performance after a repair has been effected [http://www.cl.cam.ac.uk/~fms27/papers/2009-StajanoHouWasETAL-bridges-PRELIMINARY.pdf]. By so doing, these sensor networks help reduce the time it takes to identify faults but, more importantly, predict when some piece of infrastructure will need updating or reinforcement. Similar to condition-based servicing systems installed in modern cars, infrastructure operators is increasingly turning to such sensors to reduce maintenance costs. [7] Thus, for example, studies have shown the benefit of deploying such smart infrastructure sensing systems will reach be an estimated $40M for the British tunnel market by the year 2056. [8]

Sensing systems do not only include those deployed on the built environment, but also involve people carrying their mobile phones equipped with all sorts of sensors, in so-called, participatory sensing systems. Such participatory sensing systems have been deployed in a variety of domains including disaster response (where Geiger-counter equipped phones were used to track radioactivity at higher resolution than government-owned sensors), transportation (e.g., the Waze phone app uses GPS readings on phones to update it's traffic condition dataset), and noise pollution monitoring [noisetube]. The wealth of data that is generated by such systems can be extremely powerful in solving key societal and economic challenges as they provide for better informed decision making by individual actors in such systems.

[7] http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6963375.

[8] http://www.sciencedirect.com/science/article/pii/S0968090X13000533.

Along with the benefits of all these sensing systems, comes a number of key aspects need to be considered:

1. As sensors become widely deployed in our environment, the amount of data generated will significantly increase, not only raising issues with data storage, but also giving rise to ethical and privacy issues. Along with forthcoming Internet of Things (IoT) applications, such issues will become even more pressing as data will be collected in even more intimate settings.

2. If we rely on data sourced through participatory sensing systems, how can we ensure the data is reliable and cannot be manipulated for motives other than those of the system designer?

3. How secure of such sensing systems against attacks by cyber criminals bent on collecting ever-more personal data for criminal purposes?

4. If sensors are deployed to monitor critical infrastructure, what is monitoring the sensor itself? In other words, how do we ensure the sensor networks we deploy are robust and can self-report their failures?

5. Finally, but not least, when sensors are deployed and relied upon across multiple interdependent infrastructures, identifying where faults are in such sensor networks may become a critical issue. A sensor fault in one part of one infrastructure may have disastrous cascading effects if proper safeguards are not put in place to manage these interdependencies.

The above challenges will only be met with a combination of technological innovation and appropriate governance. Specifically, we see the need to develop a coordinated approach across infrastructures to the implementation of smart sensing systems. On the one hand, at the technical level, this will ensure that operators understand how to interpret and assimilate data coming from connected infrastructures, while, on the other hand, operational measures can be put in place to ensure failures are not engendered by failing sensor systems. Going further, as systems grow in scale, it will be important to develop intelligent solutions to trawl through billions of sensor readings and uncover faults that may not be visible to the human eye. We summarise some of these ideas in the table below:

Technical	The deployment of smart sensor systems to allow for interoperability but also for resilience across smart interdependent infrastructures.
Security	Safeguards need to be put in place to protect national infrastructure against cyber attacks on sensor systems but also from inherent failures in such sensing systems.

	Participatory sensing systems need trust mechanisms to provide reliable data and to protect against manipulation.
Governance	Operators of smart sensor systems need to be equipped with decision support tools that will help them manage billions of data readings and identify faults in very complex networks.

Discussion and Conclusions