Chapter 2

DOES THE LIBERALIZATION OF THE EUROPEAN RAILWAY SECTOR INCREASE SYSTEMIC RISK?

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Abstract Recent large-scale blackouts and other incidents have shown that failures in network industries can have serious economic and social consequences. A large body of literature covers critical infrastructures (and their protection), but most of it is confined to a relatively restricted number of sectors such as electricity and information and communications technology (ICT). In addition, much of the literature discusses systemic risk in complex networks from an engineering perspective with the goal of mitigating risk using quantitative techniques.

The railway sector is a critical infrastructure that shares a number of characteristics with electricity (e.g. interconnection), but it has received little attention when it comes to systemic risk. This paper analyzes the extent to which the liberalization of the railway system increases the sector's systemic risk, a pressing question in the wake of the creation of a single European railway market. The paper also discusses the broader issue of the governance of systemic risk in the railway sector, especially since the mitigation of risk tends to be limited to risk management from a technical perspective while ignoring the institutional dimension.

Keywords: Systemic risk, European railway sector, liberalization

1. Introduction

Network industries – electricity, transport and communications – are considered to be critical infrastructures: they provide services without which modern society could not function properly. These "systems" or "systems of systems" which, by their nature, are subject to entire system risks are often referred to as "systemic" risks. Broadly, systemic risk refers to "the risk or probability of breakdowns in an entire system, as opposed to breakdowns in individual parts or components, and is evidenced by co-movements (correlation) among all or most parts" [20]. According to the Organization for Economic Cooperation and Development [29], systemic risk is the risk of failure of vitally important systems, i.e., those on which society depends, such as health, transport, environment and telecommunications.

There are arguments and some evidence that network industries are increasingly vulnerable to systemic failures. These highly complex and interdependent large-scale technical systems are subject to rapid change that poses risks to themselves while also causing disruptions through cascading effects [21, 22]. Similarly, technological change can be disruptive to established steady states, "innovation trajectories" can cascade in unforeseen ways, particularly when technological systems rapidly expand into other systems and areas or life [15].

In the extensive literature on risk in banking and finance, systemic risk is frequently and explicitly addressed and analyzed and is one of the most important concepts in the sector [18, 20]. In contrast, while safety and reliability in the network industries and critical infrastructures are extensively analyzed, systemic risk is only referenced briefly in the literature and has not been subjected to extended analysis [11, 17, 40]. Note also that power grids, telecommunications networks and railway systems face quite different risk situations due to different behaviors (physics) and different topologies. The associated term, "cascading," is used more often and is the subject of intense analysis by the engineering (and physics) community (see [35] for a consideration of small-world properties in the railway sector). However, the analyses tend to be conducted mostly through a technical lens (e.g., reliability engineering).

Because of the increased utilization of the railway infrastructure, the railway system in many countries has become quite vulnerable to disruptions [37, 38]. In most European countries, railway infrastructures are already operating at the limit of their capacity. The expected increase of "priority" trains crossing borders in Europe following the liberalization of the international passenger segment will put additional pressure on railway capacity. The unbundling of the railway sector pushed by the European Commission will add new actors and new functions (e.g., independent slot allocators), further increasing the overall system complexity. These developments, coupled with the political will to increase the share of intermodal freight transport, may put an unduly high pressure on the railway sector without any means (other than technical) to cope with it. On a more positive note, the standardization work conducted by the European Railway Agency (ERA) in the framework of the European Railway Traffic Management System (ERTMS) has forced many of the old and new European railway actors to sit at the same table and to find common answers to increasingly complex problems. However, technical standardization is only one facet of railway interoperability.

The paper argues that traditional studies on risk management in the railway sector (see, e.g., [13, 24]) should be extended to explicitly include the concept of systemic risk. The understanding of systemic risk and the answers it brings – in addition to the prevalent technical perspective – could benefit significantly from a qualitative approach. After discussing the concept of systemic risk, this paper examines its relevance to the railway sector and conducts a broader discussion of the governance of systemic risk in the railway sector.

2. Systemic Risk

This section reviews the concept of systemic risk. The discussion draws from our previous work related to systemic risk [6].

The concept of risk is not easy to delineate; in modern usage it is closely associated with the notion of hazard. While hazard is the potential to do harm, risk has more to do with "possibilities, chances or likelihoods of events, often as consequences of some activity or policy" [36]. Nevertheless, risk is usually associated with harmful outcomes and is viewed as the likelihood of harm combined in some way with the extent of the harm. Risk therefore involves two elements: (i) the likelihood or probability of a particular event occurring, and (ii) the extent of the harmful consequences of the event. The standard technical definition of risk involves quantification and is the statistical probability of the occurrence of the unwanted event multiplied by its severity [14]. However, there are extended debates on risk and uncertainty in the literature (see, e.g., [5, 7]). The scientific view is that risk is the statistical probability of harm (or uncertainty when probabilities cannot be quantified). The social science view is that risk and uncertainty are difficult to separate in most practical situations, and that the quantification of outcome probabilities is questionable.

Systemic risk refers to breakdowns of entire systems rather than their component parts. Therefore, it can be distinguished from other types of risk primarily because of its widespread and potentially damaging consequences. System breakdown risks are characterized by a break in a causal chain; the threat of system breakdown is a feature of an interconnected world and it exists at many levels ranging from local to global. Some researchers (see, e.g., [39]) further differentiate between system breakdown risks and systemic risks. Nevertheless, definitions of systemic risk often focus on the cause of the harm, the processes involved and the uncertainty in assessing the likely outcomes.

Table 1 presents the systemic risks in the financial sector. The two principal categories are macro risk and micro risk. Kroger [21] proposes a different taxonomy for the potential of triggered events, including cascading events, escalating events, common cause events and confined events.

3. Complexity and Systemic Change

Moving beyond causation towards process, there are other important distinguishing features of systemic risk associated with the inherent complexity of systems. "Complexity" is a term often used to describe the difficulties of analyzing large systems with many components. Complexity is more than just "complicated" [31]; it is qualitatively more than the difficulty involved in analyzing systems with many components and complicated behavior. Instead, it refers to systems with features that make the prediction of system behavior extremely difficult even when the properties of the component parts are well

Table 1. Systemic risk in the financial sector (adapted from [20]).

Macro Risk	A single big shock impacts all or most parts of a system – a common cause (e.g., earthquake, hurricane).
Micro Risk (Direct)	A single shock impacts only one part or a small number of parts of a system. The systemic effect is the result of a chain reaction between physically interconnected elements – a domino effect (e.g., power line cascading failures).
Micro Risk (Indirect)	A single shock impacts only one part or a small number of parts of a system. The systemic effect is the result of human interaction with other elements – the result of loss of confidence and herding or contagious behavior.

understood. Schlapfer, *et al.* [34] observe that breakdowns of complex networks are often the result of relatively slow system degradation that escalates into a rapid avalanche of component failures.

The features of complexity include nonlinearities, multiple stable states, hysteresis, contagion and synchrony, which are all features of complex adaptive systems [18]. Complex systems also manifest the characteristics of "chaos" – high sensitivity to initial conditions and outcomes that are practically impossible to predict. Abrupt regime shifts can also occur; in the economy, these can lead to inferior but stable equilibria [18]. Complexity has become a significant feature of modern scientific and technological infrastructures. Whereas scientific and technological developments proceed in an incremental manner, products and processes are added incrementally to the complex whole of science, technology, life, environment, society, politics and the economy. This creates unexpected emergent phenomena that tend to increase the vulnerability of network industries. Vulnerability has two dimensions: physical (i.e., the propensity to suffer damage when subjected to an external stress) and functional (i.e., the propensity of an element to suffer loss in functionality). These vulnerabilities can be extended to include systemic vulnerability, which is the propensity of an element to endure a loss of functionality not only due to a stress on its physical structure, but also because of its connections to other elements [27]. According to Kroger and Dietz [22], interdependencies can be characterized by their types (input, mutual, co-located, shared and exclusive); interaction levels (physical, cyber, geographic and logical); and coupling (order of coupling and tightness of linkage).

4. Systemic Risk in the Railway Sector

The notion of risk is widely used in the railway sector, but it usually refers to non-systemic types of risks. For example, the Swedish Railway Authority notes that significant risks exist within areas such as new technology for signal sys-

Table 2. Railway sector interactions (adapted from [17]).

	Electricity	**ICT**	**Water**
In	Many electrified rail systems have their own power supply but some rely on the general power grid	Disruption of ICT systems that control rail systems and manage reservations and dispatch	
Out	Disruption of coal supply to generators (typically a delayed effect)	Many communication lines follow rail rights-of-way and can be disrupted by rail accidents or attacks	Contamination from hazmat spills due to derailments

tems, EU standardization of the railway infrastructure, price trends for metals and electrical energy, very high utilization of railway capacity in urban areas and the completion of railway projects within time and budget constraints [4]. When it is mentioned, the concept of systemic risk is restricted to safety issues [16, 32, 33].

This is surprising because railway systems are part of the critical infrastructure and an interruption can have immediate and far-reaching consequences. In countries with large metropolitan areas or high population densities, there is often no alternative to railway travel. Nevertheless, the degree of criticality is moderate – the impacts of failures, losses and non-availability will in most cases be limited in scope (local to regional), magnitude (minimal to moderate) and time (hours). At the same time, the rail infrastructure depends on other critical infrastructures to varying degrees, especially energy supply and ICT systems [17]. Also, the energy sector depends on fuel transported by rail and ICT systems use data transmission lines that are often routed along rail rights-of-way. In fact, 51.7% of the electricity in the United States and 30.4% in the European Union is generated by burning coal, which is mostly delivered by rail. Table 2 summarizes the interactions between the railway sector and other key infrastructures. Note that the interactions are presented in terms of the dependence on other infrastructures (In) and the dependence by other infrastructures (Out).

Recent work [26] on critical infrastructure dependencies has revealed that most cascades originate in only a limited number of sectors (energy and ICT) and that the interdependencies occur far less often than predicted by theory. Nevertheless, the criticality of the railway sector is especially evident in the (few) cases of complete shutdown of the network. Note also that railways are an attractive territorial target as exemplified by the November 2008 "attacks" on the French TGV tracks that stranded thousands of passengers. Auerswald, *et al.* [2] opine that "in the presence of interdependencies, even if each firm is

Table 3. Recent rail failures in Switzerland and France.

Country	**Date**	**Downtime**	**Explanation**
Switzerland	6/22/2005	3–4 hours	The shutdown was caused by a power failure at 5:45 p.m. local time on a part of the track in the southern portion of the country. Around 2,000 trains and more than 200,000 passengers were affected. Financial claims amounted to around 5 million Swiss Francs.
Switzerland	2/7/2005	NA	NA
France	8/22/2004	2–3 hours	A local train dragged and broke the cable that provides trains with electricity, requiring all power to the line to be cut off.
Switzerland	1997	40 minutes	Trains were stranded for 40 minutes. Approximately 15,000 passengers were affected.

resilient, the system may still be vulnerable due to lack of coordination among, and communication between, different industry sectors." Currently, the criticality of railways is considered to be medium from the physical, operational and speed of change perspectives [17]. However, this rating should be reconsidered in the light of the fundamental transformations that are occurring in the railway sector.

4.1 Recent Railway System Breakdowns

Recent structural changes in the European railway sector (i.e., unbundling, introduction of competition and increased interoperability) raises the question if the probability of a systemic failure in the network has increased or decreased. Currently, only anecdotal evidence suggests that incidents of a systemic nature are more prevalent now than before. Compared with the extensive reports published after major electricity blackouts, relatively little information is provided by railway operators and infrastructure managers about the causes and consequences of rail breakdowns.

Table 3 lists recent failures in the Swiss and French state-of-the-art railway systems. Switzerland's railway officials blamed licensing procedures and the "not-in-my-back-yard" mentality for blocking new power lines as the underlying cause of the major electrical power outage that affected the national rail network on June 22, 2005. The Swiss power grid design offers limited opportunities to re-route power during a breakdown. The Swiss Railway has attempted to lay back-up transmission cables for three decades, but the progress has been slowed by citizen protests. Meanwhile, feeder lines from Germany are inadequate and the systems of neighboring countries are incompatible. In addition to the complete shutdown of the railway network (as in the June 2005 incident), there are also accidents of a systemic nature with relatively limited incidence (about 100 incidents per day on important lines) according to the Swiss Railway's punctuality statistics. Punctuality is defined as trains arriving at their final destination with less than five minutes delay. In 2005, the punctuality of Swiss freight convoys was 93.6% for national traffic and 74.4% for international traffic.

In our view, one of the important causes of increased vulnerability is that the railway system was designed, built and operated under public ownership in a non-competitive environment, but is suddenly expected to operate very differently in a competitive, albeit regulated, market. Networks were formed geographically at the local, regional and long-distance levels. For example, the main railway companies in Europe still make use of different signaling and electricity systems and different track gauges. Traditionally, these networks were largely separate and were owned and operated by one – often state-owned — company. Recently, larger networks have been formed by linking networks physically (same infrastructure) and organizationally (timetables and ticketing). As a result, the previously isolated railway systems that were constructed in a fairly uncoordinated and inconsistent manner have to interact with each other. The central issue is whether and to what extent these developments place pressure on operating safety margins, the transparency of reporting on safety issues and the capacity of market players and their regulators to render the vast network systems sufficiently resilient to major disruptions [29].

One way to increase reliability is to reduce the propagation of delays due to interdependencies between trains [38]. For example, the interdependencies can be decreased by reducing the running time differences per track section and creating more homogeneous timetables. When investigating railway reliability, it is important to make a distinction between primary and secondary delays. Primary delays are initial delays due to external factors, not because of other trains. These delays are caused by malfunctioning rolling stock, malfunctioning infrastructure, bad weather conditions, excessive alighting and boarding times of passengers, accidents at railroad crossings, and so on. Secondary (or knock-on) delays are train delays caused by delays of other trains; they also arise as a result of shared infrastructures and rolling stock connections. Carey [8] distinguishes between exogenous delays and knock-on delays. Exogenous delays are due to failures of equipment or infrastructure, and delays in passenger boarding or alighting (also known as primary delays). Knock-on delays are caused by exogenous delays and schedule interdependence (also known as secondary delays).

There is a well-established belief that an infrastructure capacity utilization above 75% or 80% reduces punctuality [28]. Capacity utilization above 60% is not recommended (except for rush hour traffic) because it limits railway system recovery. In fact, an exponential relationship exists between adding trains to a congested network and the expected level of network performance [12]. For the time being, the focus is on solving small primary disturbances, mainly because no timetable is robust enough to handle large disruptions without drastic real-time traffic adjustments [38].

4.2 Interoperability and Systemic Risk

It believed that the systemic risk in the railway sector could be mitigated as a result of the European Commission's ERTMS Project whose goal is to achieve interoperability of the European network by 2020. While interoperability may directly reduce a multitude of risks, it could indirectly increase the systemic risk by making the European railway network more interconnected and, therefore, prone to supra-regional disruptions. Table 4 summarizes the systemic risks in the railway sector.

Interoperability is defined as the ability of two or more systems to communicate and work together without any problems. In general, interoperability can be expected to reduce the risks of reduced performance, stability and coherence. However, interoperability needs to be understood at two levels:

- **Technical Interoperability:** This covers the technical issues of linking systems and services. It includes aspects such as infrastructure, traction units and locomotives, energy, passenger carriages and telematics applications for passenger services. Technical interoperability is directed by framing and revising Technical Specifications for Interoperability (TSI). In the railway sector, this task is taken up by the European Railway Agency, which acts as the system authority.

- **Operational Interoperability:** This is concerned with the harmonization of rules and implementations. For example, different implementations in the European rail network produce a variety of degraded situations at border crossings.

Special conditions related to rail system capacity must be considered when operating long-distance rail services. Long-distance trains often have to pass through several bottlenecks that can affect the punctuality of long-distance services as a whole. The risk of delays is greater for regional traffic than for local rail traffic because the times and distances are longer. Increasing rail traffic without increasing capacity renders the existing bottlenecks even more problematic.

5. Discussion and Analysis

While the understanding of interoperability in railway sector is only now starting to shift from a technical to an operational viewpoint, we argue that a well-performing (and safe) railway sector will require institutional interoperability. This will move the debate from the engineering domain to the political

Table 4. Systemic risks in the railway sector (based on [19]).

Triggering (crisis) event	Natural event (lightning, personnel strike), device failure (power loss), voltage collapse, protection system failure (relay system fault), inadequate right-of-way maintenance
Sector vulnerability	Growth in demand, rise in cross-border traffic, inadequate reinforcement of the power grid (failure to provide sufficient reserves), poor coordination among neighboring slot allocators, hidden failures, lack of investment in infrastructure (within and between countries)
Potential dangers	Integration of smaller systems into larger systems (facilitated by ETCS), which increases complexity and transboundary propagation of disturbances, spillover to other network industries (interdependencies)
Type of systemic risk	Large shock, direct causation and contagion, common shock contagion
Transmission channels	Interconnectedness, similar systems, high level of cross-border traffic
Requirements for contagious systemic risk	Interdependence, coordination failure between operators and slot allocators
Recent changes in systemic risk	Increased interconnection, ERTMS (interoperability), operating at the limit of capacity, market liberalization (unbundling of network elements and price)
Historical evidence of contagious systemic risk	Direct causation (more impact), common shock (less impact)
Corrective policies	Public (domestic and international) regulation

realm where harmonization is much harder to achieve. Indeed, in some European countries, the company that manages the railway infrastructure also provides railway services. In other countries, the railway market is partially or completely deregulated with different stakeholders managing the infrastructure and the railway services. In Sweden, for example, railway traffic management is performed by a neutral authority that governs the overall use of the infrastructure, while various private and public companies operate the trains that carry freight and passenger traffic.

Complexity has become a significant feature of modern technological infrastructures. System analysis shows that this comes with unexpected and unforeseen emergent phenomena that not only pose risks themselves but also cause disruptions that may cascade. Systemic risk is heightened by the fact that there is no longer a single owner, operator or regulator of the infrastructure and that, in the unbundled market paradigm, agents' decisions are based on different logics and incentives. In addition, interoperability itself may have unforeseen consequences.

Proposing techniques for mitigating risk in the railway sector is beyond the scope of this paper. However, an enhanced understanding of the systemic risk in railway systems is the first and necessary step to improve their governance. For example, it is important to avoid confusion between common cause vulnerabilities (e.g., an earthquake causing simultaneous, but unrelated effects in two critical infrastructures) and dependencies [25]. It is also important to recognize the multi-dimensional nature of dependencies. Numerous models and quantitative methodologies have been proposed to minimize cascading failures. We believe that these approaches should be supplemented by an improved qualification of risk.

Some policy recommendations for critical infrastructure protection are focused in this direction. They include upgrading and revising intergovernmental standards for security, quality assurance, education and training in order to cope with more challenging uses of the railway system (higher density of timetables, tighter safety margins) and new threats (transborder transport of dangerous goods and devices); and implementing effective technical, organizational and socio-political measures against malicious attacks that are balanced against social values (e.g., privacy and freedom of expression).

6. Regulating Systemic Risk

Much of the banking regulation in place today is designed to reduce systemic risk [1]. In many countries, capital regulation in the form of the Basel Agreements is one of the most important measures for reducing systemic risk. If one pushes the comparison with the banking sector, it is interesting to note that in the early 19th century, assuring financial stability was primarily the responsibility of central banks. The Great Depression led the United States to impose many types of banking regulation to prevent systemic risk. The recent events in the financial sector are a powerful reminder that one needs to question whether regulation, as currently implemented, actually increases financial stability. Allen and Gale [1] observe that poorly designed and implemented capital regulation can lead to increases in systemic risk. However, one of the difficulties in crafting policy to reduce systemic risk is the rarity of events and incidents that lead to complete system breakdowns. Note that system breakdown risks are not affected by societal risk perceptions or cultural views; instead, it is the "visible" breakdown risks that have to be addressed and managed.

Mechanisms in place to manage risk vary across countries [39]. Due to the interconnected nature of the risk, a national forum would be insufficient. The ideal response could be a pan-European risk management institution even if there are many factors that might inhibit its creation. Every system invites free riders and a global system that manages and enforces standards could threaten free riding. Similarly, there are always winners when a system collapses, so certain institutions may stand to gain by not participating in or by obstructing a comprehensive response to system breakdown risks.

An idealized societal response to systemic risk could be the formation of cross-disciplinary risk management agencies (possibly even situated within existing institutions). These agencies would be required to link the physical, financial and political (governance) links between the risks. One potential avenue to mitigate systemic risk would be to create a pan-European railway regulator. Currently, the European railway system is regulated at several levels. At the national level, member states have independent regulators as stipulated by Directive 2001/12. In addition, Directive 2001/14 provides that the infrastructure manager publish a network statement that contains information about the (technical) nature and limitations of the network, access conditions to the network and rules on capacity allocation. At the pan-European level, the European Railway Agency (ERA) regulates safety and interoperability. Meanwhile, RailNetEurope (RNE) is making significant progress in establishing, shaping and improving a harmonized timetabling process for international train path requests.

Several analyses that advocate a more socio-political approach suggest a move from risk management to risk governance [11, 17, 21, 31]. Another study [30] posits that complex infrastructure systems should be analyzed as "socio-technical systems" in which technical systems are not only complex but also involve the "variegated and penetrating involvement of human action, which, in all its forms, is able to affect, even critically to affect, the functioning of the system." Understanding and interpreting systems thus requires an analysis of the relationships between human actors and organizations and physical components and systems.

A comparison of the railway and electricity sectors in the context of regulatory reforms over the past two decades suggests that there needs to be a coherence between the "critical institutional arrangements that support the technical functioning of the systems" [23]. The European Union has included the notion of risk in its interoperability directives [9]. However, it is in the hands of the national safety authorities who "define, after consultation with the applicant, the scope and content of the additional information, the risk analyses and the tests requested."

The question thus arises as to whether there is a need for any special forms of governance to address systemic risk in the railway sector. Clearly, the most fundamental aspect of systemic risk is its system-wide nature and this suggests the need for a system-wide or centralized approach to governance. As discussed above, the most important systemic risks may have micro causes – such as a tree falling on a power line or a malicious individual destroying a section of track – that are propagated throughout the system. This implies that some aspects of systemic risk must be managed on a decentralized basis. Overall, the right balance should be struck between centralized and decentralized governance, depending, of course, on the type of risk.

Table 5. Coordination mechanisms (adapted from [10]).

Coordination Mechanism	**Technical Coordination**	**Institutional Coordination**
Centralized	Centralized control: Top-down	Planned economy
Decentralized	Distributed control: Bottom-up	Market economy; Classical contracting
Matricial	Integrated	Combined

In the railway sector, issues of systemic risk and the kinds of risks addressed are generally considered to be localized and bounded, albeit with severe consequences. As a result, the preparation for and coordination of such events are limited. Kunneke and Finger's work on coordination mechanisms [23] could provide a useful framework to discuss coordination with the aim of mitigating systemic risk in the railway sector (Table 5). In their view, liberalization is likely to introduce a certain incoherence between technical coordination and institutional coordination. From a technical point of view, interoperability, capacity management and system management have to be coordinated in a hierarchical manner. However, there is a certain pressure to allocate slots commercially and even to have competition among timetables. In other words, coordination problems are likely to significantly increase as a result of liberalization, which, in turn, will increase the incoherence between technical and institutional coordination.

7. Conclusions

Methods for dealing with infrastructure interdependencies must capture the complexity and interconnectedness of modern, open systems of systems; human factors; the full spectrum of threats; dynamic, non-linear emergent behavior; and the influence of contextual factors such as markets and operating environments. Systemic risk is a matter of great concern to the financial sector. As in the financial industry, research should focus on the mechanics and channels of shock transmission within and between railway networks. At the same time, more attention should be given to the regulatory nature of systemic risk. The large-scale blackouts in Europe and the United States leave a sense that the rates of occurrence of major incidents are increasing. However, additional research needs to be conducted to establish the prevalence of systemic breakdowns in the railway sector, and the relationships between increased technical interconnections, market liberalization and systemic breakdowns

The following questions should be addressed as part of a research agenda focused on systemic risk in the railway sector: How is systemic risk currently governed at the national and European levels in the railway sector, particularly in relation to technocratic and socio-political forms of management and governance? What are the strengths and weaknesses of current systemic risk governance and how might it be improved? What might governance institutions, structures and processes look like at the national and international levels in the railway sector? Which stakeholders should be involved in systemic risk governance of the railway sector? What sort of involvement should the various stakeholders have? Should the involvement be limited to information sharing or should there be close consultation and co-decision making among the various stakeholders?

References

[1] F. Allen and D. Gale, Systemic Risk and Regulation, Working Paper No. 95-24, Wharton Financial Institutions Center, Wharton School, University of Pennsylvania, Philadelphia, Pennsylvania, 2005.

[2] P. Auerswald, L. Branscomb, T. La Porte and E. Michel-Kerjan, *Seeds of Disaster, Roots of Response: How Private Action Can Reduce Public Vulnerability*, Cambridge University Press, New York, 2006.

[3] Banverket, Annual Report 2006, Borlange, Sweden, 2006.

[4] Banverket, Swedish Rail Sector Development, Borlange, Sweden, 2007.

[5] I. Bartle, Risk-based regulation and better regulation in the UK: Towards what model of risk regulation? presented at the *Second Biennial Conference of the ECPR Standing Group on Regulatory Governance*, 2008.

[6] I. Bartle and M. Laperrouza, Systemic risk in the network industries: Is there a governance gap? EPFL-MIR Working Paper, Centre for the Study of Regulated Industries, School of Management, University of Bath, Bath, United Kingdom, 2008.

[7] I. Bartle and P. Vass, Risk and the Regulatory State – A Better Regulation Perspective, Research Report 20, Centre for the Study of Regulated Industries, School of Management, University of Bath, Bath, United Kingdom, 2008.

[8] M. Carey, Optimizing scheduled times, allowing for behavioral response, *Transportation Research, Part B: Methodological*, vol. 32(5), pp. 329–342, 1998.

[9] European Commission, Directive 2008/57/EC of the European Parliament and of the Council of 17 June 2008 on the Interoperability of the Rail System within the Community, Publication L 191, Brussels, Belgium, 2008.

[10] M. Finger and R. Kunneke, Technology matters: The cases of the liberalization of electricity and railways, *Competition and Regulation in Network Industries*, vol. 8(3), pp. 301–333, 2007.

[11] A. Gheorghe, M. Masera, L. De Vries, M. Weijnen and W. Kroger, Critical infrastructures: The need for international risk governance, *International Journal of Critical Infrastructures*, vol. 3(1/2), pp. 3–19, 2007.

[12] S. Gibson, G. Cooper and B. Ball, Developments in transport policy: The evolution of capacity charges on the UK rail network, *Journal of Transport Economics and Policy*, vol. 36(2), pp. 341–354, 2002.

[13] J. Haile, Quantified risk assessment in railway system design and operation, *Quality and Reliability Engineering International*, vol. 11(6), pp. 439–443, 1995.

[14] S. Hansson, Risk, Stanford Encyclopedia of Philosophy, Stanford University, Palo Alto, California (plato.stanford.edu/entries/risk), 2007.

[15] T. Hellstrom, Critical infrastructure and systemic vulnerability: Towards a planning framework, *Safety Science*, vol. 45(3), pp. 415–430, 2007.

[16] B. Hutter, *Regulation and Risk: Occupational Health and Safety on the Railways*, Oxford University Press, Oxford, United Kingdom, 2001.

[17] International Risk Governance Council, Managing and Reducing Social Vulnerabilities from Coupled Critical Infrastructures, IRGC White Paper, Geneva, Switzerland, 2007.

[18] J. Kambhu, S. Weidman and N. Krishnan, *New Directions for Understanding Systemic Risk*, National Academies Press, Washington, DC, 2007.

[19] G. Kaufman, Banking and currency crises and systemic risk: A taxonomy and review, *Financial Markets, Institutions and Instruments*, vol. 9(2), pp. 69–131, 2000.

[20] G. Kaufman and K. Scott, What is systemic risk, and do bank regulators retard or contribute to it? *The Independent Review*, vol. 7(3), pp. 371–391, 2003.

[21] W. Kroger, Critical infrastructures at risk: A need for a new conceptual approach and extended analytical tools, *Reliability Engineering and System Safety*, vol. 93(12), pp. 1781–1787, 2008.

[22] W. Kroger and S. Dietz, Interdependencies among technical systems: The why, what and how, presented at the *European Safety and Reliability Conference*, 2008.

[23] R. Kunneke and M. Finger, The co-evolution between institutions and technology in liberalized infrastructures: The case of network unbundling in electricity and railways, presented at the *Eleventh Annual Conference of the International Society for New Institutional Economics*, 2007.

[24] C. Leighton and C. Dennis, Risk assessment of a new high speed railway, *Quality and Reliability Engineering International*, vol. 11(6), pp. 445–455, 1995.

[25] E. Luiijf, A. Nieuwenhuijs and M. Klaver, Critical infrastructure dependencies 1-0-1, presented at the *International Conference on Infrastructure Systems*, 2008.

[26] E. Luiijf, A. Nieuwenhuijs, M. Klaver, M. van Eeten and E. Cruz, Empirical findings on critical infrastructure dependencies in Europe, presented at the *Third International Workshop on Critical Information Infrastructure Security*, 2008.

[27] R. Minciardi, R. Sacile, A. Taramasso, E. Trasforini and S. Traverso, Modeling the vulnerability of complex territorial systems: An application to hydrological risk, *Environmental Modeling and Software*, vol. 21(7), pp. 949–960, 2006.

[28] N. Olsson and H. Haugland, Influencing factors on train punctuality – Results from some Norwegian studies, *Transport Policy*, vol. 11(4), pp. 387–397, 2004.

[29] Organization for Economic Cooperation and Development, *Emerging Systemic Risks in the 21st Century: An Agenda for Action*, OECD Publishing, Paris, France, 2003.

[30] M. Ottens, M. Franssen, P. Kroes and I. van de Poel, Modeling infrastructures as socio-technical systems, *International Journal of Critical Infrastructures*, vol. 2(2/3), pp. 133–145, 2006.

[31] M. Sajeva and M. Masera, A strategic approach to risk governance of critical infrastructures, *International Journal of Critical Infrastructures*, vol. 2(4), pp. 379–395, 2006.

[32] J. Santos-Reyes and A. Beard, A systemic analysis of the Edge Hill railway accident, to appear in *Accident Analysis and Prevention.*

[33] J. Santos-Reyes, A. Beard and R. Smith, A systemic analysis of railway accidents, *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, vol. 219(2), pp. 47–65, 2005.

[34] M. Schlapfer, S. Dietz and M. Kaegi, Stress induced degradation dynamics in complex networks, presented at the *International Conference on Infrastructure Systems*, 2008.

[35] P. Sen, S. Dasgupta, A. Chatterjee, P. Sreeram, G. Mukherjee and S. Manna, Small-world properties of the Indian railway network, *Physical Review E*, vol. 67(3), pp. 036106-1–5, 2003.

[36] P. Taylor-Gooby and J. Zinn, *Risk in Social Science*, Oxford University Press, Oxford, United Kingdom, 2006.

[37] J. Tornquist, Railway traffic disturbance management – An experimental analysis of disturbance complexity, management objectives and limitations in planning horizon, *Transportation Research, Part A: Policy and Practice*, vol. 41(3), pp. 249–266, 2007.

[38] M. Vromans, R. Dekker and L. Kroon, Reliability and heterogeneity of railway services, *European Journal of Operational Research*, vol. 172(2), pp. 647–665, 2006.

[39] A. Wilkinson, S. Elahi and E. Eidinow (Eds.), Section 3: Expert interviews, *Journal of Risk Research*, vol. 6(4), pp. 403–575, 2003.

[40] R. Zimmerman and C. Restrepo, The next step: Quantifying infrastructure interdependencies to improve security, *International Journal of Critical Infrastructures*, vol. 2(2/3), pp. 215–230, 2006.