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Critical Infrastructures and the Tragedy of the Commons Dilemma: Implications from Institutional Restructuring on Reliability and Safety

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Abstract
Through the influence of neo-liberal ideas, many Critical Infrastructures that used to be under public ownership have been opened up for market competition. Using the Swedish railway system as a case, this paper empirically explores whether such reforms have given rise to Common Pool Resource problems, and discusses possible implications. The results show that institutional restructuring has created challenges related to balancing the use of the infrastructure with a sufficient level of maintenance. The paper concludes that the main value of analysing Critical Infrastructures from the perspective of Common Pool Resources is the possibility of juxtaposing the way organisational and institutional interactions across scales generate both short-term gains and long-term negative side-effects influencing reliability and safety.

Keywords: Common Pool Resource; Critical Infrastructure; Reliability; Safety; Deregulation; Tragedy of the Commons

1. Introduction

Many of society's essential functions and services are provided by Critical Infrastructures (CIs), including for example transport systems, electrical power supply, and telecommunication systems (Ouyang, 2014; Boin & McConnell, 2007; Murray & Grubesic, 2007; Rinaldi, Peerenboom, & Kelly, 2001). Without the reliable function of these systems, the sustainability and overall well-being of our modern society is threatened. In recent decades, many CIs have been subjected to deregulation and privatization (Almklov & Antonsen, 2010; Clifton Lanthier, & Schröter, 2011; IRGC, 2006). This has resulted in a transformation from state-owned monopolies to a blend of public and private conglomerates. In this way, the operation and management of some of our most essential systems in society have become fragmented between multiple actors. One main reason behind liberalisation and deregulation of CIs has been a quest for increased cost-effectiveness (see e.g. Smith, Nash & Wheat, 2009). By opening up sectors that have traditionally been state-owned and state-operated for privatisation and competition, it has been argued that society will benefit by getting more value for the money.

Implications from institutional reforms on the reliability and long-term sustainability of these systems have been contested in the research literature. Whereas some studies indicate that reliability has remained remarkably high (de Bruijne and van Eeten, 2007), other studies raise concerns that re-organisations in the long run may give rise to negative side effects, e.g. due to Common Pool Resource problems (Little, 2005). Common Pool Resource (CPR) problems refer to situations where a large number of stakeholders have access to the same limited resource, and where their combined overuse can lead to diminishment, and ultimately, a collapse of this shared resource.

While CPR problems have gained significant attention in relation to natural resources, such as fishery, grazing areas, and forestry, research on CIs as CPRs has so far mainly been conceptual (see e.g. Künneke & Finger; 2009, Little, 2005) and rarely underpinned by empirical data. The purpose of this paper is to investigate whether there is empirical support for the assertion that deregulated CIs are facing commons problems, and to discuss the possible implications on reliability, safety, and sustainability of CIs stemming from these findings. Swedish railways will be used as the empirical case.

1.1 Institutional Fragmentation of Critical Infrastructures – Contested Views on the Effects on Reliability

In recent decades, the operation and management of many Critical Infrastructure systems have become increasingly fragmented institutionally (IRGC, 2006). Through the introduction of neo-liberal doctrines

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such as New Public Management (NPM), many infrastructures that used to be under public ownership have been opened up for market competition. The core ideas of NPM include the introduction of business principles in the public domain as a way of obtaining a more efficient public sector (Egan, 2010; Hood & Dixon, 2015).

Among researchers studying the effects from institutional reorganisation on reliability of CIs, completely different conclusions have been drawn. In a literature review analysing the effects of institutional restructuring on the reliability and emergency management in CIs (with a focus on the electricity sector), Antonsen et al. (2010) conclude that there is a lack of empirical studies exploring how reliability can be sustained when this is not the responsibility of one single stakeholder.

Among existing studies, Roe & Schulman (2008; 2016) argue that dispatchers, control room managers and other middle-level operators are highly important for sustaining reliability in institutionally fragmented infrastructure systems. Similar conclusions have been drawn by de Bruijne and van Eeten (2007), who used the theories of Normal Accidents (see Perrow, 1984) and High Reliability Organisations (see Weick, Sutcliffe, and Obstfeld, 1999) as their theoretical points of departure. Although these theories in many respects are incompatible, they both predict that institutional restructuring would negatively affect reliability of CIs. Despite the predicted negative effects on reliability, de Bruijne and van Eeten (2007) could not distinguish any significant decline in reliability due to institutional fragmentation, which was explained by the use of a number of organisational coping strategies, including increased use of real-time improvisation and use of informal modes of communication and coordination. Similarly, Steenhuisen and de Bruijne (2009) have concluded that restructuring of Dutch railways seems to have resulted in increased system complexity, which has made the controllers' operational processes more brittle, without negatively affecting overall performance.

While these studies have concluded that reliability has remained largely unaffected by organisational restructuring, other authors have raised concerns about the potential challenge of Common Pool Resource problems as a result of deregulation and privatisation. Traditionally, CPRs have been extensively studied in relation to natural resources, such as fishery, forestry, and groundwater basins. In the classic example of fishing as a CPR, the fish stock represents a shared, limited resource. Since fishing provides an income, each individual fisher tries to catch as many fish as possible in his or her best interest. When all other fishers behave in the same way, the Common Pool Resource is eventually depleted, leading to a negative outcome to all. Spurred by the work of Hardin (1968), who famously referred to this type of problem as the tragedy of the commons dilemma, numerous research studies have investigated ways of alleviating the challenges associated with CPRs. Most notably, Nobel Prize laureate Elinor Ostrom (1990) has presented empirically grounded results on both successful and unsuccessful governance arrangement in different types of commons problems.

CPRs refer to natural or human-made resources for which consumption of a resource unit is rivalrous (i.e. consumption by one users makes the resource unit unavailable to other users), and for which it is costly or difficult to exclude or limit users (Araral, 2014; Ostrom 1999). Ostrom (1990) has outlined two essential components of a CPR; the *resource system* and the flow of *resource units*. While the resource system represents the stock of the resource (such as the fish stock in the example given above), resource units represent what users withdraw from the resource system (the amount of fish harvested in a specific fishing ground). The CPR is sustained as long as the rate of consumption does not exceed the rate of renewal. When these variables are not in balance, for example due to challenges of coordinating or excluding users, or existence of poor investment incentives, CPR problems may emerge (such as crowding effects and congestion). While significant attention in the research literature has been devoted to how to best to govern natural resources (van Laerhoven & Ostrom, 2007), the same type of CPR problems may be facing Critical Infrastructure systems.

Many CIs have faced significant reorganisations in recent decades that have resulted in settings with similar characteristics to the more "traditional" CPRs. In particular, they typically depend on some common resource, which is threatened by overuse when many users exploit the resource. In the case of Swedish railways discussed in this paper, the common resource system corresponds to the availability of a shared rail infrastructure, which potentially suffers from overuse as deregulation opens up for increased use of the infrastructure by a multitude of private train operating companies. The resource units corresponds to the "train paths", i.e. the permission of each train operating company for running their train on a specific rail section at a specific time. Imbalance between renewal (time for maintenance of rail infrastructure) and allocation of train paths potentially leads to CPR problems.

Among existing studies analysing CIs from the perspective of CPR problems, Little (2005) presents an exploratory paper on the topic. Little notes that infrastructures to a large extent are in private ownership, and through deregulation and increasing competition the spare capacity that used to serve as shock absorbers have gradually eroded. As a result, infrastructures behave as common pool resources in the sense that they require continuous repair, maintenance and rehabilitation; otherwise they will wear out and fail eventually. While this is not in any actor's best interest, no one feels compelled to contribute to the system's long-term reliability. Little (2005) concludes that there is a lack of workable governance structure to address infrastructures holistically to ensure necessary funding.

In a conceptual paper, Künneke & Finger (2009) argue that infrastructures can be treated as Common Pool Resources, and they exemplify CPR problems in a number of infrastructures. The authors point out that institutional restructuring of infrastructures, where the infrastructure service is performed by a multitude of private and public actors, has contributed to the emergence of CPR problems. The authors speculate that CPR problems call for new types of governance arrangements, where the co-evolution between technology and institutions needs to be accounted for.

Similarly, Goldthau (2014) argues that infrastructures can be regarded as CPRs and specifically highlights the governance challenge facing energy infrastructures. In addition to the CPR problem, Goldthau emphasises two features that need to be taken into consideration for solving this governance challenge: the issue of scale (i.e. that the energy infrastructure is crossing multiple units and levels of analysis), and the embeddedness of CIs in a socio-technical context. These factors are highlighted as arguments for a polycentric governance arrangement, referring to a system comprising multiple stakeholders and centres of decision-making.

1.2 Swedish Railways as an Example

The principles and ideas relating to New Public Management has been highly influential in Swedish railways, and the motivation behind deregulation was to obtain "more railway for the money" (SOU, 2015a). While railways in Sweden used to be a state-owned monopoly, gradual deregulations have resulted in division of responsibility for different activities between multiple actors (Bårström & Granbom, 2012). Reforms in the Swedish railway system have occurred gradually over the last decades, with the first step taken in 1988 when responsibility for infrastructure provision and management was separated from train operation (SOU 2008:92). In the following decades, the operation of freight trains was opened up for competition, and maintenance as well as real estate was privatized. Over the years, the operation of passenger trains has gradually been opened for entry into the market, with the final step being taken in 2012 when the system was fully opened up for competition (see e.g. Alexandersson et al., 2012). This has made Swedish railways one of Europe's most competitive rail markets (SOU, 2010).

In parallel to the institutional fragmentation that has occurred during the last decades, railways in Sweden have had a dramatic upsurge in the number of passengers. Between 1988 and 2014 rail passenger transport has increased by 79% (SOU, 2015a). At the same time, the state-owned infrastructure continues to age and the system has faced recurring problems with punctuality, which calls for a large need for investments in maintenance (Swedish Transport Administration, 2011a). According to the national infrastructure provider, the infrastructure is aging faster than the current level of maintenance is able to counter, and a lagging need for maintenance has been built up (Swedish Transport Administration, 2011b; 2017).

The institutional fragmentation of the Swedish railway system over the last decades makes this sector an pertinent case for empirically exploring the claim that deregulated CIs run the risk of facing a commons problem. This broad question calls for a research approach involving multiple data sources. For this reason, the empirical basis underpinning this study was collected from document analysis as well as interviews. Moreover, the initial research aim was to examine how deregulations have affected reliability[2] of railway infrastructure by scrutinising data that was compiled from official statistical records. Such data is publicly available and should, in principle, be possible to use as a basis for drawing conclusions as to whether deregulations have affected reliability and safety of Swedish railways.

However, considerable difficulties for analysing and drawing conclusions from this data emerged due to the way the data had been collected and reported. For example, changes to reliability of railway infrastructure can be studied through longitudinal analyses of train cancellations, i.e. how often trains have been unable to reach their final destinations. High numbers of trains reaching their final destinations can be seen as an indication of high reliability of railway infrastructure, and vice versa. Nevertheless, the causes of train cancellations vary: Sometimes cancellations happen due to infrastructure problems (such as signal failures, which may give an indication of the infrastructure reliability), while cancellations in other cases occur due to circumstances of the train operating company (such as lack of staff or defective trains, which does not necessarily reveal much about infrastructure reliability). Since these different reasons for train cancellations are not reported, the statistical records are difficult to use as a basis for drawing direct conclusions about changes to reliability of the infrastructure system.

Punctuality of trains constitutes another potential indicator of infrastructure reliability. However, the way data on punctuality has been reported (more specifically, the definition of what has been reported as a delay) has changed over the last decades, which makes it difficult to analyse longer trends. In addition, records on punctuality only includes trains that at some point have reached their final destination; cancelled trains have not been included in these numbers. Indeed, as highlighted by the Swedish National Audit Office (2013), increased train cancellations may give rise to improved statistical records for punctuality. Also, similar to records on train cancellations described above, causes of delays may vary greatly and include everything from factors relating to train operating companies (e.g. malfunctioning trains), infrastructure failures (e.g. signals or traction power), or unauthorised persons on railway premises; all of which do not give an accurate picture of infrastructure reliability.

Taken together, this means that statistical records showing whether institutional reforms in the Swedish railway system has been accompanied with increased or decreased infrastructure reliability are insufficient, where not lacking. The same conclusion regarding the lack of trustworthy statistics and other data about the railway system is a problem that has been raised in a governmental inquiry (SOU 2015b). It is claimed that these shortcomings “have proved so serious that it has not even been possible to get an overall picture from all involved actors about what information is collected, by whom, and for what reasons” (ibid: 54, authors' translation). The Swedish Accident Investigation Board (2014) has also pointed to shortcomings in available statistics and databases that makes it impossible to determine whether the number of railway incidents has increased or not. Another report concludes that the number of derailments reported by the Transport Administration differs significantly from official statistical records presented elsewhere (SOU, 2015), which also raises questions about the trustworthiness of available data. Similar challenges in terms of finding trustworthy data series over time to study the effects of New Public Management have been reported by Hood and Dixon (2015) in their study of government modernization over three decades in the UK.

Difficulties in using official statistical records as a basis for investigating trends on reliability resulted in greater focus on document analysis as a data source. The document analysis comprised a variety of public official records such as governmental inquiries, annual reports and other official investigations, reports from agencies and authorities, audit reports, and policy documents. These documents were first briefly studied to

[2] Here defined in consistence with ISO 17574:2017 as the ability of a system to perform its intended function under given conditions of use for a specified period of time.

determine whether they fell within the area of interest for this study, i.e. if they were addressing effects from deregulations on reliability and safety. Selected documents were more carefully analysed by marking those segments of text which related to the effects from deregulations on the railway system in general, and the effects from deregulations on reliability and safety of railway infrastructure in particular. These segments were grouped under common themes (the same themes were used to analyse transcripts from interviews described below) with a special focus on whether the transcripts contained indications of CPR problems.

In addition to document analysis, semi-structured interviews were conducted with 8 respondents from various organisations in the Swedish railway sector. Since the Swedish Transport Administration is the national authority with responsibility for infrastructure provision, this organisation was considered one of the most central ones. Four respondents representing the Transport Administration were included, and their areas of responsibility included Head of Safety for Maintenance contractors (Respondent 1), Communications Manager (Respondent 2), Deputy Head of Customer-Oriented services (Respondent 3), and Traffic Control Manager (Respondent 4). In addition, the Head of Safety in three different train operating companies were interviewed. In order to obtain diversity among respondents, consideration was taken to the size of the companies that were contacted. Respondents from two larger train operating companies that can be seen as dominant on the market (Respondents 5 and 6) and one smaller company (Respondent 7) were included. Finally, the Head of Safety at one private maintenance contractor company was interviewed (Respondent 8). In addition to the formal interviews, two additional persons affiliated to the Swedish Transport Administration (Safety Coordinator and Head of Safety, respectively) were contacted, and these persons provided assistance during the process of identifying respondents and answering questions of a general character.

An interview guide was created as a basis for the interviews, and the interview questions were distributed in advance. As respondents were selected on the basis of their experience in the sector and their expected insights about effects from deregulations on reliability and safety, mainly middle and high level managers were included. In order to pay attention to the possibility that this selection was skewed towards persons with a particularly positive attitude to deregulations, interviews were initiated by letting the respondents elaborate on the effects from deregulations in both positive and negative terms. Interviews lasted between 0.5 and 2.5 hours. All interviews were transcribed, and analysed by highlighting common themes that were grouped under common categories. All quotes presented in the next sections have been translated by the authors from Swedish to English.

2. Results

In the following sections, results from interviews and document studies are presented from the perspective of whether it is possible to find empirical support that the deregulated Swedish railway sector runs the risk of a Common Pool Resource problem. As mentioned previously in this paper, CPRs are defined as those natural or human-made resources for which (1) "one person's consumption of resource units makes those units unavailable to others", and (2) "it is difficult to exclude or limit users" (Ostrom, 1999:497). These features of CPRs, often referred to as the subtractability characteristic and the excludability characteristic, respectively, are addressed in sections 2.1 and 2.2.

2.1 Subtractability

As detailed in Section 1, the main argument behind deregulating Swedish railways was to increase cost-effectiveness through strategies of privatizations and increased competition (SOU 2008). As a result of deregulations, an increasing number of train operating companies have entered the market, and in 2016, the rail system was operated by 17 passenger train companies and 13 freight train companies (Swedish Transport Agency, 2018). Consequently, a larger number of trains utilise the rail infrastructure at the same time. Inevitably, this leads to rivalry among train operating companies, corresponding to the subtractability characteristic of a CPR (as the utilisation of infrastructure capacity by one train operator reduces the available capacity for another one).

Interviews focused on letting respondents elaborate on both positive and negative aspects of this rivalry (as a way of investigating whether a generally negative stance towards deregulations was linked to a perception of large problems with reliability following deregulations, or vice versa). Results from interviews showed that, despite some initial scepticism towards deregulation of Swedish railways, all respondents generally showed a positive stance when looking back at the way the railway industry has developed over the recent decades. For example, Respondent 7 pointed out:

> "When it comes to the deregulation… In the beginning, when I was employed at SJ [before opening up the market for competition among train operating companies], I was against this; it was seen as a threat. But that was obviously linked to some kind of inherent protectionism. Now we have seen that there is a lot of vitality in the railway industry in Sweden. And many creative people who […] have accomplished a lot of things. So today I am positive to the deregulations."

In a similar way, other respondents held a positive attitude towards increased efficiency and ingenuity among private train operating companies. For example, Respondent 3 emphasised that deregulations have contributed to more flexible and innovative organisations:

> "This thing with the market forces… Personally, I think we gain a lot of positive things from the deregulations. If things had continued as before, in the inflexible manner, I think that we would not have had much development at all. It would only have cost a lot of money."

As expected, it was clear from the interviews with respondents from private train operating companies that each company strives to maximise economic benefits (e.g. profit, market share, and gross revenue) by running their trains as efficiently as possible on the most attractive railway lines and at the most attractive time slots of the day (see also Swedish Transport Agency, 2016). One of the respondents working for a train operating company (Respondent 6) explained the need for efficient use of organisational resources (including trains as well as staff) in order to maximise economic benefits:

> "There is a lot of money to gain by using trains and train drivers efficiently […]. As soon as the locomotive reaches its destination it needs to be used in another train set, and the train driver needs to drive another train, or leave his or her shift to avoid working extended hours and such things. So there is a lot of money in this for us."

The perception of increased efficiency in the industry as a whole as a result of deregulations was mentioned by most respondents as a highly positive effect of deregulations. This outcome is confirmed by analyses of the economic effects from privatised passenger operation as well as maintenance (see e.g. Odolinski & Smith, 2016; SOU, 2015), indicating that some of the key promises of neo-liberal policy have been fulfilled in Swedish railways.

However, while respondents generally held a positive view on deregulations, they also pointed out a number of challenges. One major challenge is that an increased number of trains have resulted in increased problems with available infrastructure capacity. Respondent 6 explained the challenges of allowing more companies entering the market following deregulations:

> "One side of the deregulation is that the tracks are more heavily congested. One reason is the increased traffic volume, both in terms of freight trains and passenger trains. Since there are a greater number of enterprises competing and applying for access to the tracks, it is fair to claim that a larger share of the capacity of the tracks is used compared to when a single train operator made effective systemic solutions. Now there can be a situation where two enterprises are running their respective trains directly after each other. That is something SJ [state-owned train operator at the time before deregulations] would not have done back in the days. Rather, they would have used a longer train with room for more passengers, which takes less capacity

> of the tracks in use. Now there is competition over the track capacity and the passengers, which means that the total use of the tracks is less efficient in a deregulated system.

Problems related to congestion have not only emerged as a result of an increased number of train operating companies entering the market, but are also caused by the simultaneous dramatic increase in passenger traffic during the last decades. Between 2000 and 2017, rail passenger transport increased by 61 % (JBS, 2018), which has resulted in track capacity during peak hours being fully utilized in many parts of the railway network. This is shown, for example, by the fact that the number of railway lines that have reached their maximum capacity increased from 13 to 30 between 2005 and 2010 (Swedish Transport Administration, 2011b). Between 2015 and 2017, the proportion of railway sections with the highest level of capacity utilization during peak hours increased from 33% to 44 % (Swedish Transport Administration, 2018). One of the respondents (Respondent 6) explained the problems related to the limited infrastructure capacity available:

> "There are railway sections and rail slots that are full [maximum capacity has been reached]; even at night time with [the operation of] freight trains. The problem with railways is that you are mixing trains with different speeds. If you are driving in sequence with the same speed, then you can pack the trains tightly […] but if you have one fast train in between [slower trains], then you need to stretch the sequence much more."

Moreover, as a result of increased traffic load, incidents and disturbances create substantial cascading effects once they happen, especially on the most congested railway lines (Swedish Transport Administration, 2011a). The Transport Administration points out that disturbances typically give rise to effects far away from the site where it occurred (ibid). Respondent 1 also raised this point:

> "A local disturbance in the railway system very quickly leads to both regional, and sometimes even national, consequences, that is, it affects the entire system, especially if there is a disturbance in the Stockholm area, which is the central node for Swedish railway traffic."

Similarly, Respondent 4 explained:

> "When something fails, everything goes wrong; traffic information gets wrong, the trains end up in the wrong locations, the on-board staff end up in the wrong places, etc."

Due to a heavy traffic load (and the limited opportunity to redirect traffic), the railway system has become more vulnerable to disturbances and failures (Swedish Civil Contingencies Agency, 2015). This is aggravated by some shortcomings of the governance arrangement used in the sector, which are further addressed in the next section.

2.2 Excludability

The second factor characterising a Common Pool Resource, excludability, may at a first glance seem unproblematic for railways, due to the existence of regulatory processes to control market entry of train operating companies. In theory, these mechanisms should, by relatively easy means, be used as a way of granting permission to a feasible number of trains in a way that safeguards the long-term reliability, safety and sustainability of the system. In practice, however, it appears that a higher traffic load is allowed than what is considered feasible to uphold a reliable railway service, as pointed out by Alexandersson et al. (2012: p. 10):

> "Today, a […] problem in the Swedish system seems to be that too many applications for train paths are granted, resulting in a schedule which is sensitive to disturbances. In an optimal timetable it may therefore be necessary to accept fewer applications than today."

Allocation of the so-called train paths (the permission to drive a train on a specific railway section on a specific time) is administered by the Swedish Transport Administration. The Swedish railway oversight agency has expressed concern that the Transport Administration lacks an adequate model to make priorities in the process of allocating train paths in a way that leads to a socio-economically efficient use of the infrastructure, and that makes adequate trade-offs between train operation and maintenance (Swedish Transport Agency, 2016). In a similar way, the procedures of allocating train paths have been criticised in an inquiry by the Swedish National Audit Office (2013: p. 102), claiming:

> "the Transport Administration is […] lacking a long-term strategy for allocating trains, which reserves some capacity for future needs and which also has sufficient margins to handle delays in the short term".

Accordingly, it appears that too many trains are allowed to operate the infrastructure at the same time (cf. Swedish Civil Contingencies Agency, 2015). This means that, while there are formal procedures in place to establish excludability criteria, these do not seem to take sufficient account of long-term reliability. Moreover, the problems emerging as a result of allowing too many trains at the same time are exacerbated by the way the distribution of slot times (train paths) to train operation versus maintenance operation is balanced, as highlighted by Respondent 1:

> "One of the problems we are facing, which the maintenance contractors also have raised, is that it is difficult to get access time to work [with maintenance] in the tracks. […] Now there is somewhat of a conflict between selling time slots [i.e. train paths to train operating companies] and provide access to the tracks [for maintenance operators]."

In a governmental inquiry, it is acknowledged that maintenance of rail infrastructure has been neglected while travelling has greatly increased (SOU, 2015). As mentioned above, the Transport Administration seems to face challenges in terms of making priorities and trade-offs between allocation of time for train operation versus maintenance, due to shortcomings in the model used for allocation of train paths (Transport Agency, 2016). The respondent from the maintenance contractor (Respondent 8) confirmed this problem of the governance system being (overly) generous with allowance of train operation at the expense of granting access to maintenance operations:

> "We have raised this issue for a long time. We bring this up at principally every meeting we have with the Transport Administration. It's about providing opportunities to do the work. As it is now, we are often assigned to do the work at night time, but at the same time they [the Transport Administration] want to run a lot of freight trains at night. So there is less and less time to do the work in the tracks, and the time slots available become shorter and shorter."

This comment relates to another problem encountered by the maintenance contractors; it is not only access to the tracks that is required, but also longer uninterrupted time slots that enables the maintenance contractor to carry out major jobs. This was highlighted by Respondent 8:

> "If you want to increase efficiency you need longer time slots when the tracks are closed. This does not mean that there is actually more time to do work in the tracks, it may actually be less time in total over the year, but if you have a longer period when the track is closed you have time to do several different jobs during the same time."

As shown above, several respondents highlighted the need to carry out maintenance in order to ensure reliability and safety of the infrastructure, and to raise the quality of the system that for a long time has been underinvested. For example, figures from the Swedish Transport Administration show that the number of railway lines with deviations that may develop into errors posing a danger of causing derailments increased by 181% between 2009 and 2012 as a result of reduced proactive maintenance (Swedish National Audit Office, 2013). For a long time, the infrastructure has deteriorated at a faster pace than it has been maintained since the financial resources have been insufficient to meet the overall needs, and a backlog of maintenance has been built up (Swedish Transport Administration, 2017).

Some respondents also pointed out that the maintenance is more focused on reactive recovery operations than proactive maintenance operations. As further described below, it appears that incentives to carry out reactive operations are higher than proactive operations. This clearly has negative impact on the reliability of the rail infrastructure in the long run. Respondent 8 claimed:

> "A change has occurred from preventive maintenance to corrective maintenance, where the contracts describe that […] measures [should be taken] based on the errors that are found in the infrastructure; not to prevent errors but to repair them. And since the design of the contracts and the tenders are made in that way, that is the kind of measures you get […]. As I see it, what is procured today is corrective maintenance, not preventive maintenance"

This viewpoint has also been expressed by the Swedish National Audit Office (2013), stating that the design of contracts with maintenance contractors contributes to a situation where short-term recovery maintenance is performed at the expense of preventive long-term maintenance, as higher compensation is paid for urgent recovery compared to planned proactive maintenance. Concluding this section, the deficit governance arrangement, in particular in relation to allocation of train paths and reserving time for maintenance, seems to have given rise to a problem of designing and enforcing rules of excludability capable of ensuring reliable infrastructure service in the long run.

2.3 Illustrating Elements of a Commons Problem

The results presented in the previous sections show that the characteristics of excludability as well as subtractability can be identified in Swedish railways. Deregulations have opened the railway market for competition among train operating companies. Increased economic benefits of each individual company spurs them to maximise the use of trains and staff. Combined with a dramatic increase in passenger and freight transport during the last decade, and a generous procedure for train path allocation, the infrastructure has become heavily congested. This, in turn, has led to less time for maintenance, deteriorating the quality of the infrastructure. At the same time, reimbursement to maintenance contractors is allocated in such way that more compensation is given to urgent recovery compared to mandated proactive maintenance, which further reinforces the negative feedback loop of reduced quality of the infrastructure. Taken together, these factors comprise elements of a CPR problem, which are illustrated in Figure 1.

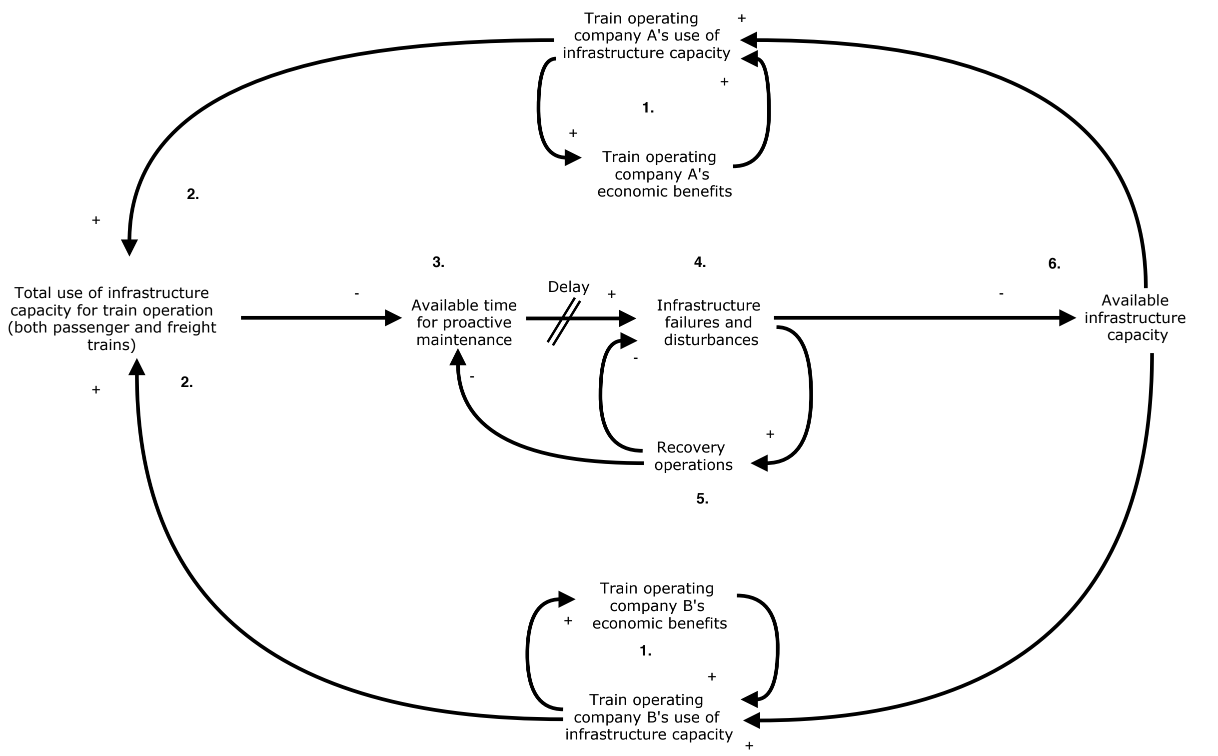

Figure 1: Causal loop diagram illustrating the elements contributing to a Common Pool Resource problem (+ referring to a reinforcing feedback loop, - referring to balancing feedback loop, and // referring to a delay)

The causal loop diagram illustrated in Figure 1 can be summarised as follows:

1. Train operating companies compete over available infrastructure capacity, granting their economic benefits. Note: Train operating companies A and B are depicted in Figure 1 as an illustration of the availability of multiple companies (passenger as well as freight train operating companies). In reality, many more companies are present.
2. Each train operating company's use of the infrastructure contributes to increased congestion.
3. Increased congestion (both day-time and night-time due to operation of passenger trains and freight trains, respectively) reduces the available time for maintenance.
4. In the longer run, reduced time for maintenance gives rise to increased number of failures and disturbances.
5. Higher incentive for short-term recovery compared to longer-term proactive maintenance, due to higher reimbursement for short-term recovery, further reduces the time and incentives for proactive maintenance.
6. Infrastructure failures and disturbances reduces the total infrastructure capacity available.

3. Discussion

From the results presented in the previous sections, we conclude that elements of a Common Pool Resource problem can be identified. The CPR characteristics identified for the kind of Critical Infrastructure studied in this paper shares many similarities with features identified for several natural resources, namely: a shared, limited resource that each stakeholder (in this case train operating companies) benefits from using, runs the risk of being overused. While benefits increase in the short-run by increased use of the shared resource (in this case available railway infrastructure capacity), this leads to negative consequences to everyone in the long run (if increased operation is not matched with necessary maintenance).

While the results presented in this paper point towards problems of managing the CPR, it should be noted that examples of both successful and unsuccessful management of shared (natural as well as human-made) resources have been presented in the literature. One successful example of management of a shared infrastructure includes the way maritime vessels navigate in the San Francisco bay by using a pooled traffic control infrastructure. As described by Roe & Schulman (2016), when the common pool communication or radar capacity is disrupted, vessel pilots mutually adjust their passage through the navigation area by converting into to a pilot-to-pilot mode of operation as a latent configuration of managing the loss of the shared infrastructure.

In papers discussing CPR problems in a CI context, which to a high extent have been conceptual, polycentric governance arrangements have been suggested as a way of solving the potential commons problems (Goldthau, 2014). This is in line with Ostrom's ideas of how to govern (some) natural resources (Ostrom, 1999). However, from our empirically grounded paper, we see no direct support for this idea in the context of Swedish railways. A major difference to many natural resources is the physically interconnected nature of railway infrastructure that spans large geographical areas, and the unique character of each resource unit in terms of spatial as well as temporal attributes (the availability of track capacity on a specific railway section at a specific time). In addition, the number of resource units in rail infrastructure can to some extent be increased by improved coordination, which is typically not possible for natural resources. As a result of these properties defining railway infrastructure, the main challenge in terms of resource management relates to balancing access for different types of users of the common resource (in this case train operating companies vs. maintenance contractors) rather than problems of finding mechanisms for excluding users, as is the case for many of the natural CPRs where polycentric governance arrangements have been suggested. Due to the limited number of studies of CIs from the perspective of CPRs, further research is required in order to draw conclusions about the generalizability of the findings presented in this study. Moreover, additional research is required to explore what lessons from successful management of natural CPRs that can be transferred to the realm of CIs, and vice versa.

One of the main values of analysing CIs as Common Pool Resources is the ways in which this perspective takes the complexity influencing reliability and safety in sociotechnical systems into account. It does so in at least two ways: firstly, by being non-reductionist (see e.g. Senge, 2006) in the sense that it acknowledges that none of the factors highlighted in this paper in isolation are critical for the sustainability of the system. Rather, it is the interactions and potential feedback loops among these factors that contribute to challenges of securing a long-term safe and reliable railway service. This can be seen in contrast to several research studies that have placed a great deal of emphasis on individual factors (such as the skills of specific groups of workers or professionals) as conditional for the reliability of the entire Critical Infrastructure system.

Along the same lines, there has been much focus on the need for increased funding to maintenance as the single solution to problems related to railway operation in many reports as well as in the public debate about railways in Sweden (see e.g. SVT, 2017). Although funding to maintenance is an important aspect, this is not the remedy to all challenges facing Swedish railways. Increased quality and reliability of railway infrastructure are achieved through the interaction of multiple actions, where increased funding to maintenance is one, but not the only. Other necessary measures include, for example, the allocation of sufficient time to do maintenance work and the use of a feasible planning tool that is able to reserve time for adequate measures. Indeed, providing only more funding to maintenance contractors in the present way of formulating contracts may lead to an over-emphasis on recovery operations (due to the existing incentive structure described above), rather than proactive maintenance that provides more substantive quality improvements.

Secondly, conceptualising CIs as CPRs highlights the fact that cause and effect in complex systems are not always closely related in space and time from each other (Erdi, 2008; Heylighen, Cilliers, & Gershenson, 2007). While institutional restructuring on the one hand may have short-term benefits (such as greater efficiency and increased economic benefit for operators), the same structural changes may be associated with long-term effects that are detrimental to the sustainability of the entire system (such as decreased quality of infrastructure elements). In recent decades, several safety science scholars have paid close attention to such time delay between changes to complex systems and their subsequent potentially negative side-effects (Dekker, Cilliers, & Hofmeyr, 2011).

One of the most popularised conceptualisations of the way threats to safety and reliability may build up and lie dormant in complex systems until they at a later stage are activated by some trivial trigger is Reason's (1997) notion of "latent failures". Whereas Reason provides limited explanation of how this type of latent failures emerge, other authors have shown empirical accounts illustrating the complexity and dynamics of the "drift towards failure" (see Dekker, 2011) in high-risk industries. Most prominently, Vaughan (1996) has given a very insightful account of the way that incremental organisational adaptations over time may lead to highly undesirable consequences. From her work trying to understand the Challenger space shuttle disaster in 1986, she uncovered a process of "normalization of deviance" (i.e. when people in the organization become so used to a deviant safety behaviour that they no longer see it as deviant). In Snook's (2000) careful analysis of the factors leading to two US fighter jets shooting down two US Black Hawk helicopters over Iraq in 1994, he describes a process of "practical drift", referring to the gradual divergence between written procedures and local practice, as one of the contributory factors to this tragic event.

These accounts point at the importance of understanding and detecting the "incubation period" of disasters (Turner, 1976; Dekker & Pruchnicki, 2013), i.e. the process of unnoticed gradually increasing risk preceding serious failures. As pointed out by Rasmussen (1997: p. 189), "court reports from several accidents such as Bhopal, Flixborough, Zeebrugge, and Chernobyl demonstrate that they have not been caused by a coincidence of independent failures and human errors, but by a systematic migration of organisational behaviour toward accident under the influence of pressure toward cost-effectiveness in an aggressive, competitive environment". Consequently, since threats to both reliability and safety in complex sociotechnical systems may emerge as a result of decisions and actions taken at multiple administrative levels far away (in space and time) from the subsequent failure (Leveson, 2011), it is important to analyse the potential for such long-term consequences when policy changes are suggested, implemented and evaluated.

In the domain of CIs, the threats of incrementally increasing levels of risk due to time lags between cause and effect have been highlighted by several researchers, e.g. with regards to a gradually reduced possibility of upholding operational competence and informal networks as a result of CI restructuring (Almklov & Antonsen, 2010; 2014). Similar concerns have been raised by Schulman & Roe (2007) as a result of the introduction of new approaches to institutional design that are potentially threating the skills and capacity of control operators to manage reliability and safety of CIs (see also Roe, 2016). These studies, as well as research undertaken in the systems safety domain (e.g. Woods, 2003) have mainly focused on changes and patterns within individual organisations that gradually lead to detrimental consequences for managing risk. This paper complements these previous studies by providing an analytical lens to illustrate the way that interactions between multiple organisations may create feedback loops contributing to threats to reliability and safety across an entire CI.

In this way, one of the main benefits of conceptualising CIs as CPRs is the possibility of juxtaposing short-term gains and unintended long-term side-effects across scales. While statistical records have yet to give any clear answers as to whether the various institutional reforms have affected reliability and safety of Swedish railways, the data presented in this paper raise concerns about the way these changes have created long-term challenges related to the ability to keep up with a required level of maintenance. Clearly, these factors constitute a significant risk to the system if they are not adequately managed.

4. Conclusions

Deregulated Critical Infrastructures may be facing similar Common Pool Resource problems as natural resources in the sense that many CIs offer a limited infrastructure capacity that each operator benefits from using. In the case of Swedish railways, elements of a commons dilemma can be found due to a combination of increased transportation demands and increased number of different operators, generous allocation of time for train operation at the expense of maintenance, long-term under-investment of infrastructure maintenance, and inappropriate incentive structures for private maintenance contractors. The main value of analysing CIs as CPRs is that this perspective explicitly takes the complexity and goal conflicts influencing reliability and safety in sociotechnical systems into account. It does so by being non-reductionist in the sense that it acknowledges the way that organisational and institutional interactions and feedback loops generate short-term benefits, but potentially also long-term negative side-effects. Although the statistical evidence is insufficient to draw clear conclusions about the effects on reliability and safety of Swedish railway infrastructure, the findings presented in this paper raise concerns about the way restructuring of the sector has created long-term challenges related to balancing the use of the infrastructure with a sufficient level of maintenance. In this regard, it is important to point out that several other CIs have undergone similar institutional reforms, influenced by neo-liberal ideals. While the goals in terms of increased efficiency and effectiveness in many cases have been reached, side-effects on long-term reliability and safety appear not to have received sufficient attention in research and practice.

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