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Resilience in systems of systems: electrified transport systems

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Abstract—

The transport system is a large system of systems which currently faces challenges because of the climate-change-induced need to decrease the use of fossil fuels. The aim of mitigating climate change is realized in many parts of the transport system, concurrently and at high pace, which brings with it many challenges for the resilience of the system. By resilience, we mean the ability of a system to adapt due to disruptions and surprises. There are numerous links between the different systems that form the transport system and the actors responsible for available choices in the system of systems need to be identified. The aim of this paper is to identify requirements for developing a method for increasing resilience in the transport system. In this study a description of the electrified goods transport system as a system of systems is developed through a combination of researchers from different areas and discussions with experts mainly in the field of transport and governance. The resulting system of systems is presented in the paper together with a list of measures that will aid the development of a resilient electrified goods transport system. The measures are divided into technology, organisation and behaviour.

Keywords—system-of-systems, goods transport, resilience, electrified transport

I. Introduction

Modern society is crucially dependent on the transport system. Due to its complexity and the need for different transport modes, different fuels and energy carriers, the different time-scales involved in traffic and infrastructure dynamics, the transport system is complex entity that is best described as a system of systems. In this paper the electrified goods transport system is used to exemplify part of the transport system, in order to understand different aspects of the system and the stress it experiences. The stress can be the change from fossil fuel into a climate smart energy system, the climate adaptation needed for an old infrastructure, the development of new transport modes and more.

The ongoing climate change has accelerated the electrification of the goods transport system; this is however not enough, it must also be designed so that it can continue to function under duress. Parts of the goods transport system are critical for the functioning of modern society. Hence, the future goods transport system must be both fossil-free and resilient. Resilience is the capability of a system to adapt to surprises and disruptions [1]. The goods transport system must be able to handle different disruptions such as extreme weather events and pandemics, but also disruptions that may occur due to the worsening geo-political conditions. The system also needs to be able to maintain its resilience through slower changes like climate change and economic or behvaioural transitions.

When analysing the transport system, the different time-scales on which it changes need to be considered. Building new transport infrastructure is a slow process that takes many years – much longer than the typical time for a transport. At the same time, new technology leads to new types of vehicles and energy.

In this paper we present some preliminary results aiming at determining how electrified goods transport systems can be designed so that they also are resilient. This will enable resilience aspects to be considered already during the design and development of future fossil-free goods transport system, instead of added on as an after-thought. In this paper we consider one aspect of the goods transport system, *viz.,* the fuel supply system and in particular infrastructure for electrified goods transport systems.

The aim of this paper is to identify requirements for developing a method for increasing resilience in the transport system. This is done by using a combination of resilience theory [1], systems of system [2] [3] and the "Seven systems" way of dealing with system engineering introduced by Martin [4]. To create a better and more developed understanding of the transport system, we use interviews with several actors knowledgeable in various relevant areas for the electrified transport system.

The paper is outlined in the following way. We first describe the transport system and define resilience. This is followed by section III where we discuss resilience in systems of systems in general and for the electrified goods transport system of systems, whereafter we draw some conclusions and list some future work.

II. Background and Theoretical approach

A. "Seven systems"

The "Seven systems" way of dealing with system engineering is characterized by the realization that system engineering needs to take account of multiple systems in addition to the one being engineered, and was introduced by Martin [4]. Martin introduces a context system, that contains a problem to be addressed; an intervention system intended to address this problem; a realization system engineers the intervention system; a deployed system that is the deployed intervention system; collaborating systems that cooperate with the deployed system; a sustainment system that provides support and maintenance to the deployed system; and finally competing systems. In addition, the context of the deployed system is often slightly changed from the original context and the distinctions between the deployed system and the developed system (intended to perform an intervention in the problem system) is made clear.

B. Systems of systems

A system of system is composed of different entities that collaborate for mutual benefit. Such elements are termed

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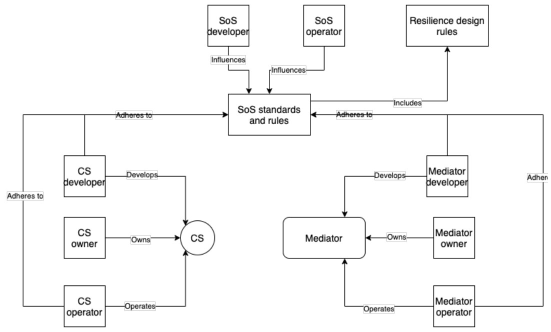

Fig. 1. Overview of (some of the) actors involved in a system of systems. CS and mediators have owners, developers and operators, who follow the SoS standards. The standards and rules are determined by the developers and operators of the SoS (which could include CS and/or mediator actors). The SoS standards include resilience design rules and operating procedures.

constituent systems (CS) [2] [3], and can be owned, operated and developed by different organisations. (In general, each constituent system will be developed/owned/operated by a consortium of several organizations.) Each constituent system has an independent purpose for existing that does not rely on the system of systems. Using Martin's terminology, there is an intended intervention for each constituent system *and* an intended intervention for the system of systems as a whole. The intervention is intended to solve an identified problem.

In addition to the constituent system, there can also be a need for mediators [5] – these are elements that help the constituent systems to collaborate, and who do not have an independent purpose without the system of systems. At any instance of time, some of the constituent systems in the system of systems will be actively collaborating while some will be pursuing only their individual goals. A set of constituent systems that are actively collaborating is called a constellation. A constellation can be seen as an instantiation of the system of systems that solves an instance of the problem. A constituent system can in principle be part of two or more constellations simultaneously. Membership of a constellation can change – some constituent systems might be involved for the entire existence of the constellation, whereas others only join for a short duration [6].

In Fig. 1 we show a simple model of a system of systems that focuses on the involved stakeholder/actors – *i.e.,* the owners, operators and developers of the constituent systems and mediators.

C. The goods transport system

The goods transport system is vital for the functioning of modern society. We need a constant flow of supplies both as individuals, as food and clothes, and as a society, as deliveries to factories and businesses to keep them running. The aim of the goods transport system is to move cargo from one point to another. In doing this, several different modes of transport are used, *e.g.,* ships, bicycles, lorries, air planes, trains etc. These systems are connected in different ways, but still often rather systems of their own. Thus, in this work, we consider the transport system as a *system of systems*, *i.e.,* a collection of independently owned, operated and developed systems that collaborate for mutual benefit.

The goods transport system is currently undergoing several transitions through the development of both techniques, organization and behavior, including changes in transport needs. This is readily apparent in the present (2020-2021) CoVID-19 pandemic crisis causing commuting to decrease sharply, while first/last-mile services increase as many people work from home and thus order direct delivery (e-shopping) instead of visiting shops. These changes of traffic flow were challenging to the transport system, where more last mile goods and less public commuting was introduced. The understanding of the future system after the pandemic is still limited.

A similar kind of shift, albeit on a slower time-scale, is the change of transport behavior related to climate change and other large movements in the society. In the city centers more people share vehicles or transport services, less parking lots are available, there is an increasing focus on smaller vehicles or walking as modes of transport. In the near future, autonomous vehicles will become part of the transport system – this will strongly affect the system. The digitalization of the transport system in the form of Intelligent Transport Systems already affects the traffic counts, *e.g.,* by informing road-users when roads are clogged, or the harbor is in a strike. The communication between vehicles and infrastructure is increasing and the need for data to be able to make proper decisions is growing, even though this need will be crucial when autonomous vehicles are an important part of the transport system.

The different time scales of changes in the infrastructure and the actual traffic is an important driving factor. The location of roads and rails have to a large extent not changed for several hundred years – the system has merely grown. The infrastructure also needs to follow similar demands as the vehicles move around and need to know what to expect from a road no matter if it is placed in very rural parts of the inland of Northern Sweden or if it is in the city center of Stockholm or Paris. Thus, changes in the infrastructure that are needed will take a long time to achieve. One ongoing such change in the infrastructure is the aim to construct electrical roads where charging of vehicles while driving on the road is possible. This aim is extremely costly and needs to facilitate the coexistence of both the vehicles in focus (which charge from the road) and traditional vehicles on the road for a long time. On the other hand, the traffic or vehicles change rather quickly, exemplified by the electrical scooters that are now common, or the anticipated autonomous vehicles. Electrical bicycles already force the municipalities of Sweden to build longer and more rural bicycle paths as commuters tend to travel further distances by bike.

The transport system also includes supporting systems – in Martin's terminology, they would be collaborating or sustainment systems. Perhaps the most obvious sustainment system is the system that ensures that vehicles have fuel. Today, the majority of this is fossil fuels, but electrification is making strong inroads. Still, both combustible fuels (gaseous, liquid, fossil and bio) and hydrogen fuel for electrical engines are used. This mix of different fuels for transport forms a system of systems for the energy supply that complicates the picture of the transport system. Fig. 2 shows a simplified view of this system of systems. The arrows show how energy can flow between different entities. A complicating factor is the possibility of conversion between different energy forms.

A large impact from the surrounding system is the climate challenge that forces us to move from fossil-based energy sources to fossil-free sources. This has a direct impact on the

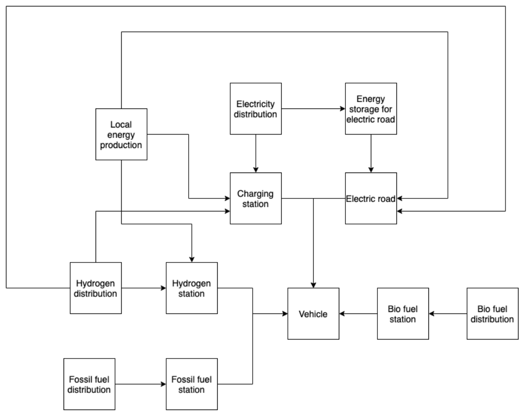

Fig. 2. A simplified view of the energy flows from different sustainment systems to vehicles in the transport system.

system since the most common energy carrier is currently fossil fuel. The energy carrier, in this context called the fuel, is to an increasing extent electricity and thus more and more vehicles are equipped with an electric engine. In a sense, this provides for more flexibility, since any energy source can be transformed into electricity before entering the vehicle. The choice of energy source is thus moved into the energy system and not partly in the transport system. Still, as vehicles cannot be modified instantaneously a large number of different fuels are present in the transport system simultaneously and thus different energy systems inside the transport system still need to coexist today and in the near future. Some of the fuels that are identified in the fossil free transport system are batteries, hydrogen fuels (used with a fuel cell either in the vehicle or at the charging station), biofuels, e-fuels and others not yet known.

As we transition into a fossil free society, the importance of electrification and other fuels – *e.g.,* hydrogen cells, synthetic fuels [7] – grows. This makes the transport system even more complex. In some ways, the situation is similar to the start of the car revolution. At this time, there was not a standard way of refueling; different companies introduced different ways. For a long time, it was standard operating procedure to have operators that filled the tanks of cars. Still, pouring a liquid into a tank can be done in several different ways even though the standard is slightly different. For electricity charging, or using biogas or hydrogen gas, the introduced risks of using a combination of different standards between the car and the fuel station is vast.

In all systems analysis work, it is important to define the system boundary – what is part of the scope of the current work and what is not. For systems of systems, this is more difficult, since the scope will be different for different involved actors. It is thus necessary to consider several viewpoints in the analysis.

D. Resilience

Resilience has become a buzz word, used to connotate systems that can withstand the challenges posed by disasters and perturbations. The concept is today used in several different contexts with different meanings [8]. It is often conflated with one or more of several related terms such as risk, robustness, redundancy [9].

Risk analysis has a long history [10], [11]. It can be exemplified by bow-tie diagrams or fault trees – the goal is to first determine events that can have a possible negative impact on the system, and then design measures that either prevent these from happening or mitigate their consequences.

For simple systems, where it is possible to predict the future behaviour of the system and list possible interferences, risk analysis suffices to ensure that a system can continue functioning during duress. However, many human-made as well as natural systems are non-linear, complex systems whose behaviour cannot be easily predicted. For such systems risk analysis is not sufficient to ensure resilience.

Redundancy, as defined by [12], is the intentional presence of auxiliary components in a system to perform the same or similar functions as other elements for the purpose of preventing or recovering from failures.

Robustness can be understood as the ability to absorb perturbations. Thus, when the set of disturbances that a system effectively can respond to expands the robustness also increase. The problem is when the system is exposed to a disturbance outside the current identified set. A robust system is therefore brittle at its boundaries [9]. When the aim is to design a system to adapts to surprises the concept of robustness is not sufficient.

In our view resilience entails more than these other concepts. Following Woods [9], we take the position that resilience means more than just robustness or just bouncing back. The essence of resilience is the ability of a system to keep functioning during duress, and in particular to be able to handle surprises. Resilience is thus defined as the "intrincic ability of a system to adjust its functioning prior to, during, or following changes and disturbances, so that it can sustain required operations under both expected and unexpected conditions" [1].

Resilience is an *emergent property* of a system. It is not provided by a single function of element of the system. One cannot add a "resilience part" to a system and expect it to become resilient [9]. Instead, the system must be designed from start to be able to adapt to new circumstances and keep delivering its intended interventions. While risk analysis, robustness and redundancy are important components of this resilience design process, they are not enough.

This definition of resilience takes into account that for complex systems, such as the transport system, it is not possible to predict all possible risks – instead there is a need to acknowledge unexpected conditions and surprises. This also goes hand in hand with the fact that we do not know what events will affect the system in the future. The definition used by us corresponds well to the INCOSE resilient systems working group definition that "System resilience is the ability of an engineered system to provide required capability when facing adversity."

E. Who is responsible for resilience?

Resilience cannot be seen as an additional functionality box that can be added to a system. Instead, is must be considered from the start in the design of the system. As mentioned resilience is an *emergent property* of a system and as such it can not be predicted on the basis of the specific compontents that make up the system.

In addition, the responsibility for making a system of systems resilient cannot be given to one actor. The emergent properties and collaboration in the system of system requires that all actors participate in the resilience engineering. This

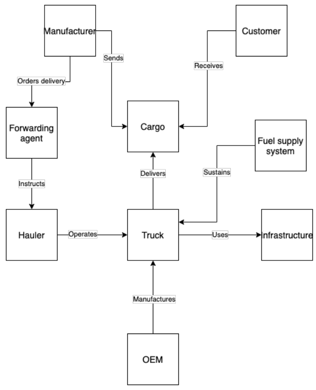

Fig. 3. Illustration of some of the actors involved in a transport mission. The transport is solved by a constellation consisting of the involved vehicles and actors.

corresponds well to the Swedish principle of responsibility for crisis management, by which those responsible for an activity under normal conditions retain that responsibility during a crisis.

III. A RESILIENT GOODS TRANSPORT SYSTEM OF SYSTEMS

A. A systems of systems description

As described above a system of systems consists of a set of constituent systems along with a set of mediators that are facilitate the cooperation in constellations. Within the transport system of systems, a constellation is a set of vehicles that together solve a transport need. Fig. 3 shows a conceptual view of actors and systems involved in the transport mission.

Depending on the scope of the analysis and the current concern of the stakeholders, what is included in the system of systems can vary. For instance, when considering the mature fossil-based transport system, it maes sense to consider the fuel supply (production, distribution, transfer to vehicles) as one system of systems, and the transport system (vehicles, roads, ..) as a separate system of systems. This simple situation is illustrated in Fig 4.

However, in the transition to electrified transport, these must be considered jointly, as parts of one system of systems. The reason for this is that both systems evolve quickly, and changes made in one of them must be taken account of in the other. If they were more stable, they could be considered parts of each others' environment. In this case, we can include also fueling or charging components into the constellation that solves a transport need. Fig. 5 shows a conceptual view of this more complicated system of systems.

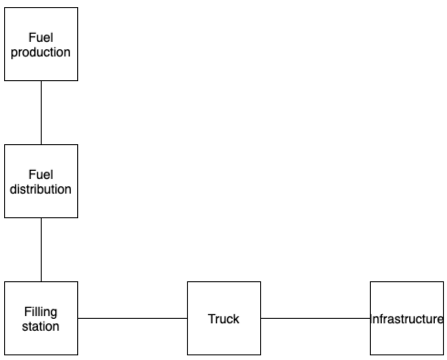

Fig. 4. Illustration of the mature, fossil fuel-based transport system.Each of the systems shown are stable and can be analyzed separately.

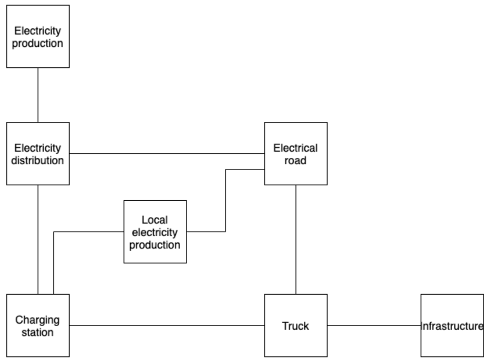

Fig. 5. Illustration of the more complicated electrified transport system. In addition to the presence of electrical roads, it is also possible to produce energy locally. An additional complication (now shown) is the fact that both batteries and hydrogen can be used to store energy for later conversion into electricity.

As mentioned above, a model of the electrified transport system must include both the actual transports and the sustainment systems. In this section we present a first draft of such a system of systems description of the electrified goods transport system. The model is based on literature and the authors' own experience from working in the field.

The purpose of building this model was both to enable systematic analysis and to provide input to subject-matter expert interviews – the model was used to facilitate responses from the experts that were then used to further refine the model. A full analysis of the interviews, which are ongoing, will be presented in follow-up work.

This paper shows the first step of creating the system of systems model from a first glance at the available data. On this firm ground the system of systems approach will be furter developed in a future paper focusing more on using the obtained system description developing abatement strategies to create a resilient electrified goods transport system.

Putting the above descriptions together, we arrive at a more complex, though still simplified, view of the electrified goods transport system shown in Fig. 6. This diagram focuses on the constituent systems and mediators, and does not show the owners, operators and developers of the elements.

For the foreseeable future, the transport system will include a mix of different fuels – hence the inclusion of both fossil, electric, and hydrogen/synthetic fuels.

In this study the system of goods transport in the transition from fossil fuels into an electrified system is described. If all future fuels and the full transport system, including changes of mobility patterns for humans, would be described, the complexity would increase. Often the severity of risks associated with the goods transport system is lower as compared to the transport of humans. This mainly relates to the risks for persons within the system, *e.g.,* extreme temperatures in vehicles that get stuck either on the rails or on roads. The harm of goods is naturally not given the same attention. Still, the interaction between goods transport and mobility is large and will in the future grow even larger as the same vehicles can be used for both kinds of transport.

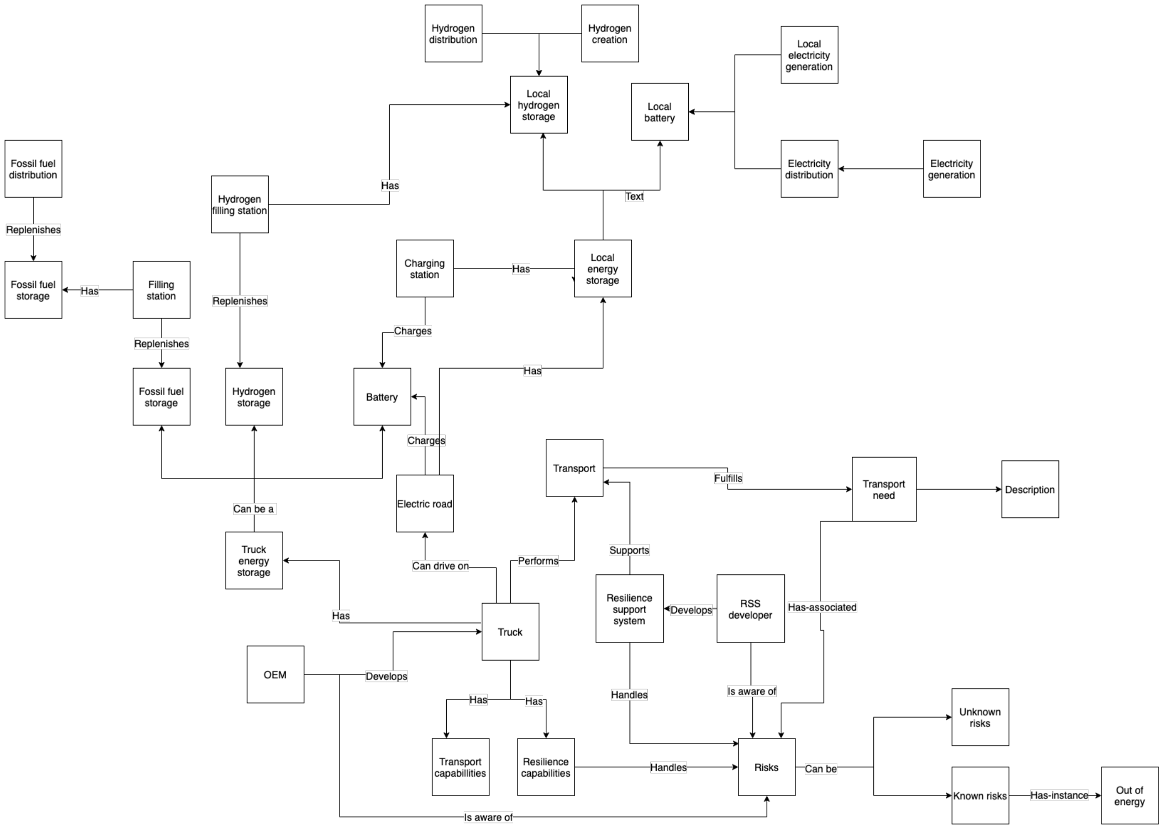

Fig. 6. A system of systems model of the fossil-free goods transport system

B. *Resilient goods transport system of systems*

On a high level, the design and operating principles that can be changed in order to improve the resilience can be divided into three areas: technology; organization; behaviour. Note though that there is considerable interaction between the different categories.

1) *Technology*

The technology components that enhance resilience can be either on a constituent system level or on the system of systems level. Examples of the former could be the inclusion of spare batteries in cars. Also, providing the technical functionality to not only charge car batteries but also use the car batteries as a reservoir for the energy system when production is smaller than energy use is a technical component on the constituent system level that must be matched with technical, organizational and business resilience components at the system of systems level. (For example, business models, rules for when car batteries can be used, rules for how much energy must be left in the car (for emergencies etc).)

In addition to the changes in constituent system technology, it is also possible to introduce new technology solutions as the system of systems level. This would take the form of adding functionality to an existing mediator or introducing a new one. One example is adding a refueling vehicle (a vehicle with large batteries) that can drive to vehicles that need to be recharged and are far away from a charging place.

The inclusion of means of local energy production is also an example of a technical solution. This is a design change on the constituent system level – the charging system is a part of the system of systems. But there is also a need for corresponding changes in the organizational/business components at the system of systems leve – technology resilience measures cannot be studied in isolation.

2) *Organization*

More important are the changes needed in organizational structure. These can be the introduction of new roles or functions at the constituent system or system of systems /constellation level (ie, new kinds of mediator, new task for component of CS, …). There is a strong need for training to enable stakeholders to internalize actions to be taken in case of crisis. For this, new rules and doctrines are needed. All stakeholders involved in the electrified goods transport system should take part in regular exercises.

3) *Behaviour*

As for the other areas, behaviour changes can be at the SoS or CS levels, but an additional complication is that the behaviours of users as well as other stakeholders is also important.

The introduction of new technologies and new transport modes pushes the change of behaviour or culture. In the electrified goods transport system a large part of the behavioural change is introduced by e-shopping, where at present the cargo is delivered in a shop and taken to the end station by the buyer to a system where the cargo is delivered directly at the private home. Thus the goods was until now owned by the customer during the last transport from the store to the customers home, and the new system change the ownership of the goods when it is delivered at the home of the customer. This introduces new modes of transport and a dependence on a system delivering most cargo all the way home, as compared to the present system where most people transport the goods the last mile themselves.

C. Towards using systems thinking-based methods for resilience analysis

As argued in this paper the transportsystem is a system of systems, and hence there is a need for systems-based methods when analysing it. It is also a large socio-technical system with many stakeholders involved, each of which can have several roles. The interaction between actions taken by different stakeholders needs to be taken into account when analysing the system. Further, there is a need to be able to include actions/measures that can be taken.

To analyse and improve the resilience of the system, we can use a model based on control theory to identify risks, opportunities, possible actions, and who should perform each action. Resilience is thus viewed as a control problem. One example of such a model is STAMP (System Theoretic Accident Model and Processes) which is an accident causality model based on systems theory and systems thinking [13][14]. One reason for using STAMP-based methods is that these naturally enable focusing on the actions that can be taken by different actors.

IV. Discussion

In this paper, we briefly discussed how resilience must be modeled as an emergent property in systems of systems with a focus on the future electrified goods transport system. We argued that when studing complex systems it is not enough to only focus on robust components and perform risk analysis to designe a resilient system of systems. We then introduced a simple classification of measures that could be applied to the system of systems to make it more resilient. The different responsibilities of owners, developers, and operators of the constituent systems of a system of systems was briefly discussed.

We described some of the challenges associated with electrified goods transport systems, and presented different views of the combined system of systems associated with it. The description of the electrified goods transport system was developed during interviews with experts in the field and constitutes a start of the path towards a resilient goods transport system.

The are ample opportunities for research in the field of resilience engineering for systems of systems in general and in the domain of electrified resilient goods transport systems in particular. The interplay between design rules for different kinds of constituent systems and mediators needs more exploration, in particular to take account of the need to keep business-critical aspects of designs secret. Resilience is an emergent property of the system of systems. Hence more work is needed to produce models that can be simulated to detect their emergent behaviours is needed..

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