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Abstract

System resilience is the ability for complex, dynamic-adaptive socio-technical systems to absorb and rebound from trauma or stress, and to avoid "jousting with dragons" where results are uncertain and often fatal. In a safety context, the term "dragons" originates from Professor David Woods at Ohio State University and the relatively new field of Resilience Engineering. Dragons are an illustration for the consequence of "surprise" as depicted in ancient seafarer maps that filled the seas beyond the known boundaries of the ancient world with fire-breathing dragons, and certain death. In a modern day sense, dragons represent the unintended, and often unforeseen and unpredictable, consequences of crossing operational boundaries that are difficult to identify precisely, are often influenced by various actors, and are continually changing. In particular, due to the complex, dynamic-adaptive behaviour of systems, classic statistical metrics used in current Safety Management Systems (SMS) no longer allow us to predict the next undesired event. We need to change our focus and find new ways of capturing the faint signals of impending failure. This will require structural, psychological and social changes in the way SMSs work. In this paper, I will address the issues of understanding and managing complex, dynamic-adaptive systems through the quality of resilience, and how to avoid "jousting with dragons" in the transport sector using a Resilience Engineering lens.

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1. Introduction

Resilience Engineering is a multi-disciplinary, theoretical approach to designing and managing complex, dynamic-adaptive socio-technical systems, and has become recognised as an alternative to traditional approaches to safety management (Hollnagel, Braithwaite and Wears, 2013). From its beginning in 2006, Resilience Engineering has expanded its focus on how to make high-risk, socio-technical systems more adaptive to internal and external threats and disruptions to system functioning through the quality of resilience (Hollnagel, Woods and Levesen, 2006). Woods (2016), one of the original promoters of the Resilience Engineering movement, has argued that focusing on systems is not enough, and that instead, we should be focusing on Tangled Layered Networks (TLN) of Interdependent Units. This is particularly relevant when we look at different transport sectors where different actors, on multiple levels, have varying levels of influence and control, and where operational boundries are often blurred. And in some cases, boundries may overlap, and create unexpected surprises. This places new challenges on modern safety management systems. In this paper, I am not advocating replacing safety management systems, but instead to make them more resilient, and to shift the focus on safety to more interactive methods to either predict, or at least to detect in advance, the next undesired outcome. In this manner, we will be better prepared to take proactive adaptive actions to either avoid, or at least minimise the impact of undesired events.

But what is resilience, and what is the meaning of resilience in a "systems" context? The word resilience has been used rather loosely across many academic areas of interest. Resilience has been described as "the ability of a system to adjust its functioning prior to, during, or following disturbances so that it can sustain required operations under both expected and unexpected conditions" (Hollnagel, Braithwaite and Wears, 2013, p. xxv). Others describe resilience as "network architectures that can sustain the ability to adapt to future surprises as conditions evolve" (Woods, 2006, p. 5). In any case, many have argued that we need to take a more systems approach to safety in high-risk environments (Larsson, Dekker and Tingvall, 2010).

Before we can address this quality of resilience, we must first understand the context within which we view it. Obviously, how we describe the transport sector, and where we draw the boundries, are important for addressing various mechanisms of resilience, including: history, the role of culture and leadership, organisational structure, regulation, rule creation and rule enforcement (compliance), environmental factors, industry boundries, evolving technologies, economics, and societal issues. And this list is not exhaustive. In this paper, I will draw the boundry initially at the global (society) level for each sector since societal demands permeate the entire transport system through changing environments, society, governmental intervention, regulatory agencies, organisations, special interest groups, and individuals. The transport sector consists of related industries experiencing rapid - but asymmetrical - technological change and different levels of economic growth globally, which vary greatly in their design and purpose depending on the form of transport we are addressing. This also leads to different types of risk, and potential for disaster. I will focus mainly on four transport areas: air (manned and unmanned), rail, maritime, and road transport. Each has its own history, culture, legacy structures, and relationships to safety performance, and each has its own approach for managing safety. In addition, I will take a look into the future of autonomous vehicles which will introduce new and exciting challenges within every facet of the transport sector. Keeping that in mind, I will present each area separately, analyzing the challenges for the future through a Resilience Engineering lens. And, finally, this paper will challenge the traditional approaches to safety management by shifting the focus of "trial and error" learning, to

more interactive SMSs that capture the weak signals of drift into surprise by engaging the natural adaptability of the human element at both the leadership and individual levels.

This opens up another area of controversy. What is safety in a transport sector context, and what are the desired results from a resilient transport safety management system? Each sub-category of the transport sector struggles with different safety-related issues and deals with these issues in different ways. Air transport, at one end of the spectrum, has dealt with the catasprophic consequences of meeting the Dragon on many occasions, and has experienced the resulting high-profile media coverage and after-action consequences for the entire industry, examples include: Tenerife, Überlingen, German Wings, and Malaysia Airlines Flight 17. Each of these accidents was different in nature, but each brought changes to the aviation industry, and identified potential safety areas of improvement. But each also came as a surprise. Through a dedicated safety focus, and widespread use of safety management systems, the aviation industry has responded to each accident, and has achieved tremendous safety improvements, over time, yet surprises still occur. It can be said that the aviation industry has even approached levels of safety performance described as "ultra-safe" (Amalberti, 2001, p. 109) defined as a mythical barrier of one disastrous incident per 10 million events (10^{-7}). But, as I will discuss later in the paper, as organisations approach *ultra-safe* levels of performance, fewer and fewer traditional metrics are available to help predict future events upon which to take timely, proactive corrective action (Lofquist, 2010). Road safety, at the other end of the spectrum, continues to be an area where improvement needs to be made across a wide range of safety-related issues. In 2010, over 1.24 million people were killed on the world's roads, and this number is predicted to increase in the future (WHO Report, 2013). Unlike the aviation industry, road safety is experiencing a negative safety trend, and this trend is expected to increase into the future due to global expansion of motor vehicle use into poorer economic regions that lack the proper infrastructure, and appreciation for safety culture, to support this growth unless significant improvements in safety management are achieved.

It is clear that there is plenty of room for safety improvement at both ends of the transport spectrum, and everything in between, but as we approach the mythical "ultra safe" level of safety performance, we can only achieve significant improvement through new approaches to safety management that create safer transportation networks at multiple levels. This requires a new understanding of the environment within which we operate, and create transport networks that engineer resilience into systems at the structural, psychological, and social levels, and places less focus on statistical analysis of what goes wrong, and more focus on identifying and understanding how, and why, things work in a dynamic-adaptive world (Hollnagel, 2014). This requires a new set of soft-metrics captured and reported by operators in the system detecting the faint signals of drift into failure (Dekker, 2011). Finally, we need a better understanding of how to detect operational boundaries in every transport sector, and learn how to take adaptive measures before "jousting with dragons."

This paper is structured in the following way - first, I will present a review of the safety literature with a particular focus on the idea of resilience and Resilience Engineering. Second, I will present a short presentation of each transport sector in turn: Air, maritime, rail, and road transport. And, third, I will combine the analysis into topics for discussion and recommendations for improving current safety management systems by engineering resilience at several different levels within each transport sector.

2. Literature review

In this section, I will present a review of the academic literature appropriate to addressing the most important themes relevant to modern Safety Management Systems (SMS) in the transport sector. In particular, I will try to define resilience and resilient qualities from environmental, organisational, social, and individual perspectives, including both structural and individual resilient qualities.

2.1. Safety

Safety, as a concept, is difficult to define and even more difficult to measure (Lofquist, 2008; 2010). Safety performance is measured most often through the occurrence of undesired outcomes or failures, usually with some form of adverse consequence. These are described as incidents, accidents, near-misses, etc. Based on the level of consequence, we often investigate these undesired events in different ways to find the so-called "root causes," a guilty party, and someone to blame/punish (Dekker, 2012). We then change operating rules and regulations, implement new procedures, kick off "safety campaigns," and erect new barriers so that a similar type of event will not happen again. Bourrier (1998) argues that "too often, organisational analyses are carried out only after a catastrophe has occurred. While very interesting, this perspective has serious limitations, and it is always easier to explain and reconstruct an event after they have taken place" (p. 133). In many cases, our linear attempts to address complex control issues simply repositions ourselves for the next undesired event and leads to new surprises. This requires a new, forward-looking focus that is more concerned about why things work as desired than why things fail (Hollnagel, 2014).

Unfortunately, the level of consequence from undesired events often colours our impression of these events, and shapes our reactions. The greater the consequence, the more effort we expend, and the greater the political consequences in trying to understand what went wrong. Even more disturbing are the number of undetected events that cause no consequence whatsoever, but could have. In fact, most, if not all, "undetected" events present faint signals that are either not noticed, or noticed and not acted upon in a timely manner. And without consequence, we often ignore the signals. In any case, undesired events are really just "normal" outcomes allowed by system design or evolution (Perrow, 1984). There are two main reasons for undesired outcomes and surprise. The first is due to "bounded rationality" (Simon, 1957), and the second is the nature of complex, dynamic-adaptive socio-technical systems. Systems are designed with the best intentions for desired (expected) results; however, we are limited in our ability to understand every possible outcome of the designed system. And whether through "loose" or "tight" coupling (Perrow, 1984) in the form of feedback loops and delay (Forrester, 1961), or simply through system evolution/adaptation, crossing operational boundries, and meeting the Dragon are possible - though undesired and unexpected. Even if we could understand every possible outcome at any given point in time (good and bad), the system will continue to evolve, allowing unexpected outcomes that are also undesirable. That is the reason why we need to engineer resilience into systems at several levels. Resilience is the ability to absorb the degradation/evolution of a system drifting towards failure (Rasmussen, 1994; Dekker, 2006, 2011) in a proactive manner by allowing extra time to detect and adapt before crossing an operational boundry leading to failure, and returning to some new level of temporary equilibrium. This can be achieved through resilient structural design (robustness), and/or through engaging the adaptive capacity of the human element in socio-technical systems. This will be addressed further in the next section.

Safety, in a transport sector context, usually focuses on safe and efficient transport of people and/or goods across, or through, varying mediums such as air, land, sea, and/or space. Space, the final frontier, will not be covered in this paper but space-related accidents, such as the Challenger and Columbia space shuttle accidents, have shaped much of our understanding about the political and economic factors causing drift into failure (Vaughn, 1996; Gehman, 2003). In the transport sector, cheaper, faster, farther (Woods, 2016), and, most importantly, safer - are key buzzwords

describing our transport goals, both now, and into the future. So we need to look at safety from an expanded strategic business context where safety is one, but not the only priority affecting business decisions (Lofquist, 2010). Rasmussen (1994) has contributed with the notion of organisational drift towards accidents under economic competitive pressures. So these goals are potentially conflicted; they influence performance results in unexpected ways, increase risk, and often lead to new unexpected forms of failure and surprise. As mentioned above, this is, unfortunately, often addressed in a reactive manner based on adverse events that produce some form of negative consequence such as injury, death, loss of economic value, or damage to the environment. A good example is the implementation of a two person rule following the Germanwings crash. Though this was more than just a "knee jerk" reaction, a single pilot in the cockpit was not the cause of this accident, and two persons in the cockpit would not necessarily have stopped this event from happening as evidenced by several commercial airline "pilot suicides" over the past 30 years where two pilots were, in fact, present in the cockpit (BEA Report, 2016).

Without a clear definition of safety, operationalising safety measures directly is difficult, particularly as we approach "ultra safe" levels of performance. And without an accepted definition of safety, we are forced to focus on the absense of safety through the recording and analysis of incidents and accidents. But recent studies have argued "that the traditional safety metrics for measuring safety through the reporting of incidents and accidents, though important inputs, do not fully capture the true safety state of an evolving organisation, or even the industry as a whole, and are, at best, lagging indicators" (Lofquist, 2010, p. 1523). Other safety studies have found that the quality of defining and reporting incidents and accidents vary across industries, from organisation-to-organisation, and even between units within organisations, so that these measures are often unreliable, or at least difficult to defend, statistically (Cabrera and Isla, 1998; Pidgeon, 1997). So, we need to shift our focus away from traditional "trial-and-error" learning techniques, where the cost of learning can be too high, to a more interactive learning paradigm that builds resilience into system design, and engages and leverages the natural adaptability of the "man-in-the-loop."

2.2. Safety Management Systems

Whether or not we can agree upon a universal definition of safety, we can agree on the undesirability of its absence (Reason, 1990). To achieve acceptable levels of safety performance, and to ensure a systematic approach to the management of safety, we have designed Safety Management Systems (SMS). SMSs are conceptual models that represent our understanding of our environment, and form a framework that emphasises the dynamics of safety management in our field as a process with activities and tools. They are designed to manage all of the unintended risks to life, health, property, and the environment (Hale, Heming, Carthey and Kirwan, 1997). Traditionally, safety is essentially built into a system to cover the entire expected life cycle of the system. This includes anticipated performance criteria based on performance models. But in the words of Sterman (2002) "we must understand that all models are wrong, and humility about the limitations of our knowledge" (p. 501). In a complex, dynamic-adaptive world, nothing is exogenous (Sterman, 2002), and nothing is completely predictable, so models have their limits. Box and Draper (1987) agree, but added that "essentially, all models are wrong, but some are useful" (p. 424). As an example of all models being wrong, or at least imprecise, in 2010, I presented a conceptional safety management system model to illustrate a simple model of how safety management systems work, as depicted in Figure 1, below (Lofquist, 2010).

Figure 1. **Safety Management System: A simple model**

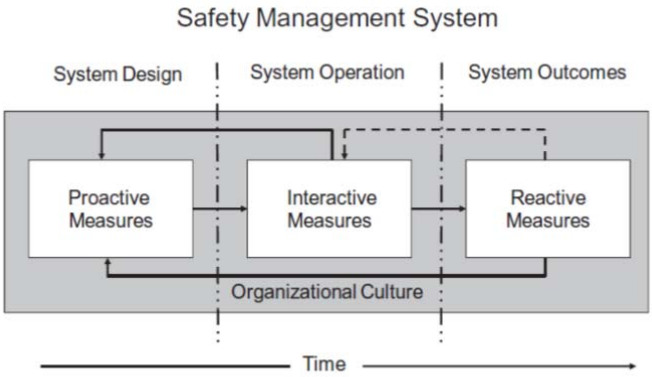


Fig. 1. Integrated safety management model.

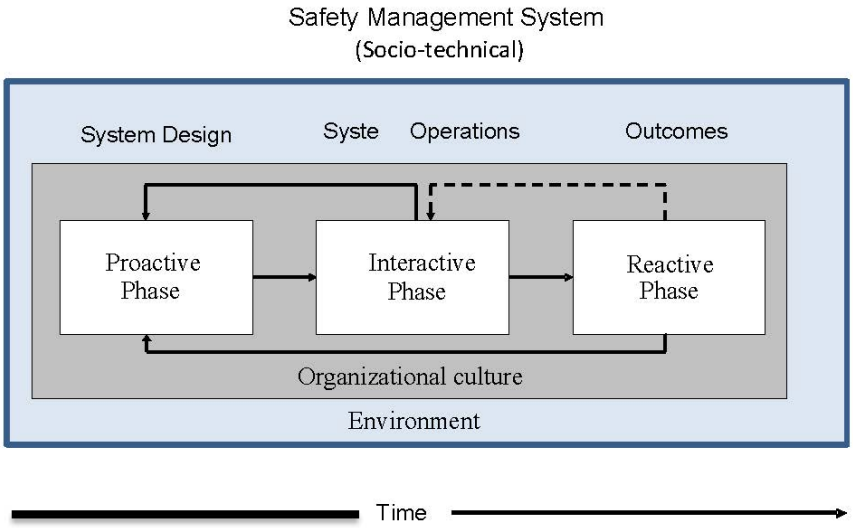
The model shows how SMSs work, conceptually, from early system design, to intended/expected operations, and finally, to system outcomes in three temporal phases (proactive, interactive and reactive) represented by the three white boxes. The time arrow below the diagram indicates the dynamic nature of the entire system under continual evolution. In reality, the contents of each box is quite complex in themselves and vary from industry-to-industry within the transport system. For example, the proactive measures box includes initial system design and redesign, including desired outcomes, system processes, guiding rules, routines and regulations, safety measurement targets, individual skill sets and education requirements, etc.

The arrows related to the individual temporal phases within the model represent how organisations historically react to undesired outcomes depending upon level of consequence. Traditional safety management systems monitor the system outcomes primarily in the reactive portion of the model and, depending upon the desirability of the outcomes, and consequence, react by adjusting system performance through two paths. The dotted arrow from the reactive to interactive boxes represent typical reactions to undesired events (surprises) with little or no consequence such as minor injuries or inconsequential, near-misses. The normal reaction is to change a rule, adjust a procedure or routine, initiate a new safety campaign, or create a barrier. The solid, bold arrow, from the reactive to proactive boxes, represents major system adjustment or complete system redesign due to significant consequence. This occurs when an organisation encounters a major undesired event involving high level organisational or societal consequence. These undesired events usually take the form of a major collision, an environmental disaster, or severe injury/death. A good example of the difference can be seen in the Columbia space shuttle accident. During the life of the space shuttle program, space shuttles were regularly impacted by foam from the rocket boosters during launch. The Columbia Accident Investigation (Gehman, 2003) revealed that this occurrence was even more regular than previously realised. As the operational consequence of a foam strike in earlier missions was relatively minor (or unnoticed), the focus shifted from safety of flight concerns, to a maintenance function of repairing, replacing and/or re-coating scratched portions of the shuttle post-flight (dotted line in Figure 1). However, with the destruction of the space shuttle Columbia, and the death of seven astronauts upon reenty on 1 February 2003 due to impact of a large piece of rocket motor foam during launch, the entire space shuttle program was put on hold for two years, and a complete redesign of the rocket boosters was conducted. This action is depicted by the solid bold line from the reactive phase to the proactive (design) phase. The main learning point from the model is that we can no longer afford to wait for significant consequence to effect system changes (adaptation), but instead, we need to pick up the faint signals of impending failure already in the interactive phase of operations (rocket motor foam), and follow the solid line from the interactive to proactive phases and initiate proactive changes on a system level prior to major surprises. This shift in focus from what goes wrong (Safety I) to what

goes right (or at least detecting the faint signals of impending failure through resilience) has been labelled Safety II (Hollnagel, 2014). Safety II will be explained in more detail late in the paper.

However, despite its usefulness in understanding how safety management systems work, the original Safety Management Systems model proved to be too simplistic because there is much more complexity involved than just the internal processes within organisations. First, the effects of organisational culture on performance are greater than expected as evidenced in prior safety studies (Weick, 1993; Vaughan, 1996; Gehman, 2003). In particular, understanding the balance between people and technology is critical to improving SMS performance, and will vary significantly across high risk industries. And for this paper, the socio-technical balance will vary across the entire transport sector. The other important addition to the model addresses the influence of the external environment which is, in fact, not exogenous, and plays an ever-increasing role in organisational performance. Organisational pressures created by external stakeholders were well-documented in the study of the Challenger launch decision (Vaughn, 1996). This understanding resulted in a new version of the safety management system model that stresses both the socio-technical nature of modern systems, and that all systems are imbedded within an environment containing structural factors, and many influential stakeholders. The revised SMS model is depicted in Figure 2.

Figure 2. **Revised Safety Management Model**



It is the potential usefulness of SMSs that we are focusing on in this paper, to identify and understand their limitations, and how they might be improved to achieve even higher levels of safety performance considering both internal and external factors. As mentioned, the revised safety management model (Figure 2) is conceptual and theoretical showing temporal dimensions and actions that will vary from industry to industry. Each portion of the model is complex by themselves, and can be understood in further detail by reviewing Discussion Paper No. 2016-xx (Maurino, 2017). And finally, much like the term safety, there is little consensus about what an SMS actually is, and how it should be managed (Bottani, Monica and Vignali, 2009). For the remainder of the paper, I will focus how we might introduce resilience into each part of the Safety Management System model depicted in Figure 2, above.

2.3. Resilience

The word resilience comes from the Latin word “resilire,” and means to “jump or leap back” (Fletcher and Sarkar, 2013), and was first introduced by Holling (1973) as the ability of a system to absorb disturbance and maintain stability. Traditionally, resilience has been viewed from two main perspectives. From a physical science perspective, resilience describes how materials resume their shape after movement or alteration, returning to the original equilibrium state (Lazarus, 1993;

Luthar, 2000). From a social-ecological perspective, resilience is "the capacity of a system to absorb disturbance and reorganise while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks" (Walker, Holling, Carpenter and Kinzig, 2004, p. 1). Others claim that system "resilience for any particular function can be measured based on the ability to persist under varying levels of stress and uncertainty in the face of disturbances" (Ayyub, 2013). In either case, resilience has been traditionally defined and measured through two main concepts: adversity and positive adaptation (Fletcher and Sarkar, 2013; Luthar, Sawyer and Brown, 2006; Luthar and Cicchetti, 2000). Adversity, in particular, is controversial in that it is a negative loaded concept that would preclude situations where potential stress, novelty, and impending adversity are possible, but not yet present. This is also where faint signals of impending failure are possible to detect. From a systems perspective, this requires a new definition of adversity in a complex-adaptive system that will allow the system to capture the faint signals of impending danger as they drift towards operational boundaries and adaptation prior to meeting the dragon.

A newer approach to resilience, closely related to the social-ecological definition, is the concept of organisational resilience. Organisational resilience is a broader construct, and addresses improving decision making by encouraging diversification of capacities so that organisations can be responsive to uncertain future events (Bernard, 2004; Suddaby, 2010). This requires several levels of resilience that include: states, traits, processes, and outcomes (Fletcher and Sarkar, 2013). In addition, organisational resilience recognises organisations as complex, dynamic-adaptive social-technical systems experiencing continuous change, and where the new equilibrium state from adaptation is uncertain and variable. Organisations achieve resilient performance by building resilient qualities at the structural, social and individual (psychological) levels. However, in the transport sector, our analysis transcends the organisational level as there are many actors and stakeholders directly and indirectly involved in operations both within and outside the organisation. This is where Woods' (2016) idea of Tangled Layered Network of Interdependent Units is helpful. For example, for road safety to be effective it needs the cooperation of many stakeholders. It needs the development of a national road safety strategy involving the government, as well as participation by the transport, health, education, and law enforcement sectors (WHO Report, 2013). These will, of course, vary depending upon the transport branch upon which we are focusing.

In this paper, I am interested in defining and identifying potential resilient qualities within each transport sector, and how operationalising these qualities at the societal, structural and individual levels might improve safety performance. This includes structural qualities and individual behaviours that can detect and adapt to system degradation or change prior to collapse/failure. These qualities include, among others: national and local innovations, flexibility, improvisation, adaptability, education and training, and problem detection and solving.

2.4. Resilience Engineering

The field of Resilience Engineering began in 2006 through an assembly of multi-disciplinary safety experts. The objective was to understand what safety is, and why accidents happen. The focus has expanded over time as a paradigm for safety management in high-risk environments that investigates how to help people cope with complexity under pressure to achieve success (Hollnagel et al., 2006, p. 6). It also focuses on the nature of systems and networks under stress. A key feature of modern, high-risk industries, such as found in the transport sector, is that they can be defined as complex, dynamic-adaptive social-technical systems, and where people can positively affect outcomes. This includes leadership and culture. But high-risk industries are also highly controlled and regulated both internally and externally due to the potential for disaster. The focus on control creates a problem as static rules, regulations, and procedures are not capable of adequately controlling dynamic-adaptive systems under continual evolution. This leads to a gap between safety rules and procedures as imagined and enacted (Hollnagel, 2014). In addition, Lofquist, Dyson and Trønnes (2016) found that different sub-cultures, both within and outside of an organisation, interpret rules through different lenses, resulting in different levels of rule compliance, or even non-compliance. A classic approach to monitoring these industries is to investigate what goes wrong, such as: malfunctions, errors, failures, incidents, accidents, and near-misses in a backward looking

fashion to identify the so-called "root causes" and, often, human error. This approach was mentioned earlier, and has been called Safety-I (Hollnagel, 2014). In effect, safety is measured indirectly through its absence and not its presence (Reason, 1997). But history has shown that we can no longer live by this backward looking focus. Instead, Erik Hollnagel (2014) has introduced the concept of Safety-II, where the focus has shifted to what goes right, and how to capture the faint signals of systems evolving/drifting towards collapse. This is similar to shifting our focus to the interactive phase of the SMS model presented earlier (Figure 2).

This can be done by creating mindfulness within individuals at all levels of the organisation/system that remain sensitive to the possibility of failure (Weick and Sutcliffe, 2006; Sutcliffe and Weick, 2013) while focusing on why things go right. For most instances within the transport sector, we are not really talking about individual organisations, but a tangled network of individuals, organisations, and entire industries, where the boundaries are often blurred (Woods, 2016). The key is to understand why things go right, how things work, and manage performance variability from a system's perspective, not just constrain it (Hollnagel, 2014). Yet, understanding how the system works, the desired outcomes, and detecting the faint signals of system degradation is not enough, there must also exist a structure that supports the means for deviation and adaptation "on the fly." This requires a new paradigm supported at all levels that focus on how entire systems work.

Important to the field of Resilience Engineering is the understanding of the complex, dynamic-adaptive nature of systems that cannot be precisely described, specified, codified, mechanised, or controlled. This leads to outmoded theories of control and standardisation of work, and where each innovation makes the system more complex and less tractable (Hollnagel, 2014). This is particularly relevant for the transport sector experiencing continual innovation and change, while simultaneously addressing economic pressures. In addition, the transport sector is quickly moving into a bold, new world where fully- and semi-automated vehicles, in all transport sectors, will operate side-by-side with other forms of manned transport. This will require a completely new global concept on transport safety.

One of the strengths of Resilience Engineering is that it addresses both the blunt and sharp ends of the system together, and looks at how well a system can handle disruptions and variations that fall outside of the base mechanisms/model for being adaptive as defined in that system (Woods, 2015). Through resilience, we can build systems that are stable, sustainable, robust, and can survive unexpected challenges. Another important concept within the Resilience Engineering paradigm is to design systems with graceful extensibility. Graceful extensibility is a core concept that integrates a variety of the ideas such as detection of operational boundaries, surprise, brittleness, saturation, varieties of adaptive capacity, forms of adaptive breakdown, and others (Woods, 2016, p. 1). Graceful extensibility is the opposite of brittleness where systems suddenly collapse when a boundary is crossed. This collapse often comes without out clear warning and comes as a surprise. Complete surprise often results in improper reactions to recover, if recovery is possible. The space shuttle program, for example, was not prepared to repair shuttle wing damage due to rocket form damage in space during the Columbia flight. Wing inspections and repair capabilities were normal on subsequent space shuttle flights once the program continued. Graceful extensibility pushes operational boundaries, or improves performance approaching boundaries, and allows more time to notice and react to impending surprise through adaptation. So in essence, graceful extensibility is the ability for a system to extend its capacity to adapt when surprise events challenge the operational boundaries (Woods, 2016). Resilience also means understanding when systems are approaching operational saturation constricting options and adaptability. So to achieve resilience we need the ability of a system that is capable of adjusting its functioning prior to, during, or following changes and disturbances so that it can sustain required operations (performance) under both expected and unexpected conditions (Hollnagel et al., 2006).

2.5. Safety culture

One area often mentioned, but not fully understood in a safety context, is the role of safety culture in high-risk environments where there is still a great deal of debate. An important factor for understanding safety management systems is the role of the socio-technical balance within the system. In the transport sector, in particular, culture needs to be looked at from many different levels and across many diverse countries, and even across different regions within those countries. Culture, as "the way we do things around here" (Schein, 2010), is very difficult to define and measure. In the transport sector, we need to understand the effects of culture on several different levels: global, national, industrial, organisational, and even down to the cohesive operational unit, and individual. Each of these levels contribute to culture in different ways. There is also a great deal of debate as to the usefulness of culture, as a construct, as being too broad and abstract, or whether climate, as a more localised, snapshot phenomenon, is a better construct. But whether it is culture or climate, it is real, it affects how different situations are interpreted, and leads to distinct patterns of behaviour that differ across transport sectors. Therefore, we need to try to understand what culture is, and where it comes from.

Culture is created through the daily interactions within in a group of actors interfacing with their immediate environment. Actors absorb the actions that work and discard those that do not, so context is important. Overtime, these patterns of successful interactions are assimilated into ones subconscious and become what Schein (2010) calls deep-seated, underlying assumptions, and form the basis by which we interpret information, react and behave. Culture also influences new members as they are integrated into the organisation. On a national level, this includes national history, language, religion, education systems, and accepted norms of behaviour. On an industrial level, this includes the industrial history and development, current infrastructure design, educational requirements, guiding rules and regulations, and accepted norms of performance. On an organisational level, culture is influenced by the history of the company, by the leadership, and the way the company competes within the industry. And finally, at the group level, culture reflects the adaptation of the individual actors within the group as they attempt to achieve organisational goals. The role of culture will naturally vary across the four transport sectors studied in this report.

2.6. Leadership

The role of leaders, and leadership, are often neglected in the study of safety. However, leaders are important for setting the strategy of the organisation (or society), establishing a vision and direction for the future, creating or modifying culture which influences the types of behaviours and results expected of its members. Some argue that culture cannot be managed (Grote, 2012), which is true, however, culture can be influenced through leadership actions at many levels. Unfortunately, changing culture, due to its nature takes both consistency and time, and often fails to achieve desired results. In addition, here culture can be examined at several levels: national, organisational and unit dimensions. Unfortunately, we often only focus on leadership actions as the defined lines of interaction within a control context, and not on the individual interactions or relationships themselves.

There are no universally agreed definitions of leadership. Leadership can be viewed as both a noun (as in the different roles leaders play and the lines of control), and as a verb (as in what leaders do). As a verb, leadership is the "art" or "behaviour" of the leader, and involves an individual who leads others through some form of leadership actions (relationships) that influence others toward a common goal through expected behaviours. Leadership must also be studied at many different levels and within many different contexts. At the organisational level, it is through interactions with individuals (relationships) that leaders promote resilient qualities, and this includes leaders at every level of an organisation, and can greatly influence organisational results. Resilient behaviour requires leadership behaviours that promote different psychological states such as autonomy, self-efficacy, self-esteem, organisational commitment, and job satisfaction. These states contribute to extra-role behaviour and better performance. Wilson and Ferch (2005) believe that to achieve

resilience at the organisational level, leaders must create an accepted shared vision of the desired workplace culture.

In the transport sector, the leadership function is rather diffuse. Leadership as a noun describes the hierarchy of decision making and rule creation from the individual operators, through the leaders of the organisation, and to the external stakeholders. Leadership as a verb is how leaders at every level communicate and interact with subordinates at other levels. This type of leadership can either promote or hinder resilient behaviours that can directly affect safety performance. This will also vary greatly between the different transport sectors. Again, the examples of the difference between air and road transport are a good starting point.

3. Industry analyses

In this section, I will briefly investigate each of the transport sectors in turn, with a particular focus on safety and how Resilient Engineering practices might lead to safety performance improvement. I will focus on three areas of the revised Safety Management System model (Figure 2) – the environment, socio-technical system, and process. Each of the transport sectors addressed in this paper can be characterised as having strict regulatory frameworks, with different histories, varying levels technological design, and different operational training demands. I will start with a presentation of the air transport industry, as it is arguably the most safety-conscious industry of the four transport industries presented in this paper. I will then present the maritime and rail industries, and end with the road transport industry, which is arguably the sector in most need of safety improvement, and where the use of a deliberate safety management system is unclear.

3.1. Air transport industry

Man's obsession with flight dates all the way back to 1000 BC when the Chinese first invented the kite (www.loc.gov). In the following years, man continued to pursue flight through balloons, airships and gliders. The first manned, powered, sustained, and controlled flight is credited to Orville and Wilbur Wright in 1903. Despite the fact that they only travelled 120 feet (36.5 metres) in 12 seconds on the first try, controlled manned flight was a reality (www.grc.nasa.gov). An important aspect of this great achievement is that Orville and Wilbur both survived. However, from its inception, the dangers of manned flight were clear, and many of the early flight pioneers died in efforts to push the flight envelope. The world's first scheduled passenger airline service took place on 1 January, 1914, when the St. Petersburg-Tampa Airboat Line carried a single paying passenger between St. Petersburg and Tampa, Florida (www.space.com). In the 102 years that followed, commercial air transport has expanded its passenger capacity significantly, and the International Air Transport Association (IATA) predicts that international air carriers will transport 3.6 billion passengers in 2016 (www.iata.org).

Although modern air transport is considered safe, it is not without risk, and is a good example of pushing operational envelopes, with many examples of encountering the Dragon. Although the marginal rate of growth in traffic has increased between 2009-2013, the accident rate has decreased consistently to a level of 2.8 accidents per million departures (ICAO Safety Report, 2014). But there are many operational challenges ahead as the issues such as: airspace density, air traffic control restructuring, pilot aging/shortages, introduction of remotely piloted (autonomous) vehicles, etc.

Environment

From a single commercial aircraft in 1914, to over 100 000 civil and military flights per day in 2016, the sky is becoming increasingly crowded (www.icao.int). In an environment that must balance safety with other key issues, such as: cost, environment, capacity, and efficiency, the challenges are many (Safety intelligence for ATM CEOs White Paper, 2013). One of the main arguments for achieving better safety performance is to achieve safety intelligence defined as safety knowledge, particularly for the top leaders in the industry. This is also important from a Resilience Engineering perspective where leaders can both create resilient environments through leveraging technology, changing safety cultures, and by promoting resilient behaviour through leadership actions that are more relationship oriented instead of control based. The air transport industry is an excellent example of a complex, dynamic-adaptive system under increasing stress, and it is only through knowledge and understanding that leaders can address future challenges by designing resilience into both the organisational structure, and resilient behaviours amongst its actors at various levels.

The air transport industry is experiencing the introduction of more complex technologies and integration issues, increasing economic pressures, capacity limitations in both aircraft and qualified personnel, environmental challenges, and aging infrastructure, just to name a few. This requires continual learning and transformation. It is primarily the top leaders across the entire air transport industry that must first, and foremost, possess the appropriate knowledge, and have the skills to use that knowledge. Second, leaders must use this knowledge to manage the overlapping relational complexity issues between governments (airspace), regulatory agencies (domestic and international), airports, air navigation control agencies, airlines, pilots/crews, air traffic controllers, and military aircraft operations, etc. And this is a continually evolving process. Leaders must anticipate the future challenges and adapt to these challenges across boundaries by building resilience into what is essentially more of a Tangled Layered Network of Interdependent Units (Woods, 2016), than a system. The first step is for leaders to understand the concept of resilience, and how to design resilience into the system.

Socio-technical system

The man-machine interface issues within air transport are very complex, continually adapting, and diffuse, with many professional layers both within individual aircraft, different airlines, air transport organisations, and across different support organisations. Historically, the air transport industry has evolved from relatively slow, simple flying machines with only a few paying passengers and some mail, over short distances, to a mix of fast, highly technical and complex aircraft carrying hundreds of passengers, as well as tons of cargo across the globe. These changes have also increased the opportunity for large scale disaster such as experienced during the Tenerife air disaster (Weick, 1993).

Navigational rules have also changed significantly over time as navigation moved from primarily visual cues during daylight hours, to improvements in navigational technologies such as radio aids, inertial navigation systems, and Global Positioning Systems (GPS). These changes brought with them both new opportunities, and new challenges and risks. For example, early air navigation was much similar to driving on roads (or even following roads), or flying point-to-point using visual cues such as landmarks. This required flying in good weather with clear visibility. The introduction of radio navigation aids allowed aircraft to be operated in most weather conditions where visibility was reduced, and at night. With better aids to navigation, aircraft could use invisible jet routes in the sky defined by navigational aids, and where safety was primarily achieved through flying at different altitudes depending upon direction. Flight planning allowed aircraft to insert pre-planned routes that enabled aircraft to continue to the planned destination safely if radio contact was lost, which was a rather common occurrence during the early years of flying. This was, however, quite costly and inefficient. Instead, direct point-to-point flight is much more economical in both time and cost, but it increases the risk of mid-air collisions, and requires greater control. This control was partly achieved by installing internal transponders signalling aircraft positions to air traffic

controllers who then guided aircraft through commands to pilots in both direction and altitude. Using transponders was also much more effective and reliable than primary radar. However, as traffic volume increased over time, controlling so many aircraft simultaneously became more difficult, and near misses became more common. To address this new risk, planes were equipped with internal transponders (Traffic Collision Avoidance Systems – TCAS) that would warn of the proximity of other aircraft directly during a conflict, and provide collision avoidance cues. This added a new level of resilience to flight navigation. But technology alone is not always enough as shown in the Überlingen mid-air collision that took place over Germany on the 1st of July, 2002. In that accident, two experienced flight crew, assisted by an experienced Swiss air traffic controller, and state-of-the-art TCAS equipment, tried desperately to avoid a collision in full sight of each other (at night) for just under one minute, only to fail and collide at 36 000 ft. killing 71 people (Johnson, 2004). In this case, it was a combination of managerial cost saving initiatives, work station overload (due to scheduled maintenance), unclear procedures, and culture that contributed to the accident.

The role of the pilot/crew, though still essential, has evolved as automation of various portions of flight has increased. And this has also had a positive impact of safety performance. However, as air transport vehicles become more and more automated, and possibly even completely autonomous, the pilot's role has, and will continue to change. This has also changed the role of the pilot in other ways. Instead of manual control, the pilot's role has become more of a system monitor prepared to take over if needed. With longer flights, and less hands-on control, pilots must deal with new challenges in the cockpit. The other key actor to safe flight is the role of air traffic control. The air traffic controller provides clearance to enter the jet route structure, coordinates traffic, and supports safe flight. But as rules change and the air traffic volume increases, the coordination problem is becoming more complex.

Process

From a safety management process perspective, the air transport industry is quite advanced and doing quite well. From lessons-learned during the early year accidents, and industry-wide actions taken after major disasters over the past decades (reactive phase), there has been a steady focus on air transport safety improvement, both from a structural and behavioural perspective. Proactive measures to improve aircraft performance and reduce pilot workload are a continual process. New navigation technologies are being introduced creating more direct routing possibilities and reduced costs.

From a resilience engineering perspective, the system is robust but continually under evolving conditions and where crossing operational boundaries are unforgiving. New technologies need to be integrated into legacy systems to provide increased graceful extensibility and earlier identification of drift into failure. But that is not enough, integration of new air transport capabilities, such as semi-autonomous/autonomous and unmanned flight vehicles will significantly increase the complexity of operating in the global airspace. Other areas of interest are the potential changes that could be achieved through implementing "Big Data," and real-time transmission of flight data. This will be addressed further in the discussion section of this paper.

3.2. Maritime transport safety

Maritime transport plays a major role in international trade, and is an integral part of the international transport system (Zhang et al., 2014). Due to the tremendous potential for major economic loss and environmental impact, safety is a major concern. Concern for maritime safety has been with us since men first went out onto the sea in ships. This is clear from the stories from ancient times (www.imo.org). In the early periods, ships rarely left sight of land as they lacked navigational techniques, and were extremely vulnerable to changes in weather and uncharted waters. Views on maritime safety were different from nation to nation, and largely depended upon the skill levels and the bravery of individual captains. Even as ships became more seaworthy and navigationally advanced, there have been many, high profile accidents that have highlighted the inherent dangers of maritime transport. The Titanic, Herald of Free Enterprise, and Prestige

tragedies are good examples (Yang, Wang and Li, 2013). But that being said, the maritime safety rates worldwide have improved significantly over time with total losses per thousand vessels being reduced from 9.7% in 1910 to 1.5% in 2009 (Lloyd's Register, 1910-2010). Yet despite the inceased understanding of the environment and improvement in navigational techniques, high profile losses still occur.

It wasn't until 1993 that the International Maritime Organisation (IMO) first adopted the Safety Management Code (ISM) that required all shipping companies operating certain types of vessels to establish safety management systems (Batalden and Sydnes, 2014). The new maritime safety analysis processes essentially introduced formalised approaches for quantification of risks (Yang, et al., 2013).

Environment

The maritime transport environment is extremely dangerous and unforgiving. The greatest dangers to ships include: weather related hull-breach (Prestige 2002), capsizing (MS Rocknes 2004), at sea collisions with other ships (USS Kennedy/USS Belnap 1975), Icebergs (RMS Titanic 1912), grounding (Exxon Valdez 1989/Costa Concordia 2012), onboard fire (Scandinavian Star 1990), sinking (MS Estonia 1994), and watertight door failure/capsizing (Harald of Free Enterprise 1987). Each of the events above had a series of process failures that resulted in the accident. Other more recent dangers include: piracy and terrorist/military attack.

Maritime accidents can have catastropic effects, such as: loss of life, significant economic loss, and/or major environmental damage. However, with the implementation of the Safety Management Code, ships are more prepared for adversity than before. Improvements in nagivational systems and weather reporting accuracy, ships are less likely to travel off course and more prepared to avoid adverse weather.

Socio-technical system

The nature of the socio-technical systems on ships has evolved over the years. The role of the captain as master of the ship with unlimited power and authority, and ultimate responsibility, is still relatively intact. But the economics and industry competition has created changes in sailing schedules, less time in port, and has reduced manning requirements through automation.

Process

From a safety management process perspective, the maritime transport industry has improved over the past years. Reporting procedures have improved significantly through the implementation of the safety management code. In addition, much of the fleet have been modernised giving better manoeuvring control and more precise navigational systems.

3.3. Rail transport safety

Finding a comprehensive global history of railroad transport development is a difficult task. It seems that each nation has its own romantic relationship to the early beginnings of rail transport in their country, and the significance that rail travel has had for growth and prosperity. Trains have been the work horses of industrial growth in many nations, and in some nations, the means for national expansion. Rail transport differs from all of the other transport sectors in that they are dependent upon a very complex, integrated, fixed-track system, that include single track lines supporting two way traffic, and an elaborate signaling system to ensure safety. Unlike aircraft that can change direction or altitude at will to avoid potential collisions, two opposing trains on the same track have few options.

Railroad safety has been an important focus area for as long as trains have existed due to the potential for disaster. Trains transport more than people. Trains also transport cargo, and is the primary means of transporting hazardous cargo across long distances. Trains are vulnerable to

different safety threats such as: boiler explosions, derailment, head-on collisions, run-away trains, level crossing accidents, etc. In 2014, 1 928 people were killed or seriously injured in European Union member states from 2 213 train accidents (Eurostat, 2015). Two types of accidents caused 99% of the fatalities: rolling stock in motion or level-crossing accidents. Rolling stock in motion is a major issue for track personnel performing maintenace and equipment update in the rail cooridor. In the US, accidents related to human error and track defects account for two-thirds of all train accidents, while trespassing and highway-rail grade crossing incidents account for 94`% of all rail-related fatalities (Federal Railroad Administration, 2016). Despite these numbers, the number of fatalities per billion passenger-kilometers is considered quite low, and where passenger safety has improved significantly over the past decade (Eurostat, 2015). Rail trainsport is considered relatively safe compared to other overland transport.

Environment

The rail transport environment consists of a complex network of integrated tracks supporting both national and international rail service. Rail transport law in Europe and surrounding countries is contained in the Convention concerning International Carriage by Rail (COTIF), and is applicable to signatory states. The aim of the Organisation is to promote, improve and facilitate, in all respects, international traffic by rail, and conformity by member states. In the US, the equivalent is the Federal Railroad Administration (FRA) under the Department of Transportation.

Socio-technical system

In the US, the Federal Railroad Administration (FRA) has accepted that regulation and compliance alone will not improve safety, and have started a program of working with industry management and labour to develop a rail safety culture that goes beyond regulations to performance-based risk management programs tailored to each railroad's operating environment (FRA, 2016). In Australia, Sydney Trains has incorporated several initiatives to include drivers in the creation of rules and safety goals (Groves, 2016).

Process

As part of a safety improvement program, the FRA has implemented the following programs: Training Standards for Safety Employees; Passenger Equipment Safety Standards for High-Performance Rail; Train Horn Rule to Mitigate Community Impact While Maintaining Safety; Use of Cameras on Trains; Revisions to Signal System Reporting Requirement and Hours of Service Recordkeeping; and Drug Testing for Maintenance-of-Way Employees. In Sydney, Sydney Trains has involved incorporated Just Culture to improve both employee involvement in operational policies and created a better environment to promote reporting (Groves, 2016).

3.3. Road transport safety

The earliest record of roads date back to mesopotania (Iraq) 4000 years B.C. (www.fhwa.dot.gov). Road transport safety is a high priority in most nations as safety levels remain low despite national efforts to improve safety performance. In addition to over 1.24 million persons reported killed on the world's roads in 2010, another 20-50 million sustained non-fatal injuries (WHO, 2013). However, due to the variation in the quality and quantity of road accident reporting, it is impossible to estimate the real costs of road accidents. Research has identified five major risk factors for accidents: speed, drunk driving, and the use of motorcycle helmets, seat-belts, and child restraints. Each of these factors have been shown to either reduce the likelihood of accidents or reduce the severity of the consequence of an accident.

Compared to the previous transport sectors, road transport is less regulated on a global basis, and legislation and enforcement can vary from country to country, and even state to state within countries. In addition, road infrastructure varies greatly from region to region. Road transport is similar to the rail industry as it has a relatively fixed route network, but the flexibility of the road

network produces many more opportunities for accident situations. Also roads and rail have common crossing points where coordination is required. To achieve safety through national road safety plans, the WHO (2013) has identified five areas of improvement: road safety management, safer roads and mobility, safer vehicles, safer road users, and post-crash response.

Environment

The road transport environment varies dramatically across regions and within countries within regions. Maintaining a road network infrastructure to support safety is a prime concern. The WHO has recommended several approaches to reduce this figure. First they recommend adopting and enforcing new and existing laws to reduce speeding, curb drinking and driving, decrease mobile phone use and other forms of distracted driving. It calls for putting in place infrastructure that separates pedestrians from other traffic (separated sidewalks, raised crosswalks, overpasses, underpasses, refuge islands, and raised medians), and create pedestrian zones in city centers by restricting vehicular access, and improving mass transit route design. Another method to improe safety results is to mechanically enforce lower vehicle speeds (speed bumps, rumble strips and chicanes), and improving roadway lighting. The WHO also recommends developing and enforcing vehicle design standards for pedestrian protection, including soft vehicle fronts. And finally, there needs to be better organising and/or further enhancing trauma care systems to guarantee the prompt treatment of those with life-threatening injuries when accidents occur (WHO, 2016).

Socio-technical system

The road transport network is a very complex system-of-systems with many dimensions. There are several different classes of vehicles including: trucks, buses, cars, motorcycles, and bicycles. Each having different driving characteristics and each having different vulnerabilities. In addition, the road transport network shares the roadways with pedestrians. Pedestrians pose a particular problem as over 270,000 pedestrians die each year accounting for 22% of the 1.24 million persons that die in traffic-related deaths.

Process

Road safety has developed gradually over hundreds of years. From simple conflicts between animal drawn carts and horses with pedestrians and cyclists, to today's conflict with high speed vehicles (trucks, cars and motorcycles), the challenges have evolved. For many years, priority has been given to vehicles, and this is how infrastructure has developed, but as evidenced by the WHO (2016), conflicts with pedestrians continues to be a global problem, and this will continue to grow as more and more vehicles enter traffic infrastructure lagging behind the demands for safety for non-vehicular traffic.

Traffic laws have developed differently in different countries. An interesting contrast is how countries approach parking. In Australia, for example, it is illegal to park against traffic, and in many areas backing into parking spaces, and remaining within designated parking lines, is required. In England and the US, on the other hand, cars park in either direction on the street. In Norway, where the offshore industry has mandated that employees back into parking spaces for safety reasons, Norwegian law does not require this. In addition, it is common to see cars parked rear first in parking space at shopping centers facing against traffic. This is in effect, the illusion of safety and not safe practice itself. Dekker (2011) argues that road safety suffers from a linear approach to safety in accident investigations where finding the guilty party is the goal.

4. Measuring the effectiveness of Safety Management Systems

In this paper, I have argued that designing resilience into organisations will lead to improvements to safety performance and effectiveness. However, it is clear that the task of building resilience into Safety Management Systems is a difficult one, and requires a major paradigm shift in our approach to safety, and that includes how we measure safety. Each transport industry has evolved differently over time, and use different SMS designs due to the differences in their histories and the socio-technical systems in place, so measuring the contribution of resilience to effectiveness will require different types of measures to complement those already in place.

An important question is how to measure the effectiveness in Safety Management Systems. This is a difficult task for several reasons. First, what do we mean by effective? We have already seen that as safety improvements push organisations toward ultra-safe performance (Amalberti, 2001), there are fewer and fewer traditional metrics to enable leaders to predict the next undesired event (Lofquist, 2010). Nothing to measure makes it difficult to determine whether SMSs are effective or not, and certainly not useful in predicting the next undesired event. And how safe is safe enough? And second, are there alternative metrics available to fill this gap? Current SMSs are quite sophisticated, and capable of collecting and analyzing vast amounts of safety data. Yet, dispite the improvements in data collection and analysis techniques, these remain essentially lagging indicators, they fail to predict surprises at the boundaries of operational design, and this is particularly true for those that fall outside the original design of the system. These surprises are often one-off events, and completely unexpected. Yet, in hindsight, we find that we should have seen the signs of impending disaster. The Germanwings tragedy is a good example.

Also, as we approach ultra safety levels of performance, there are fewer and fewer hard data points to collect to enable us to predict future events. The reasons for this have been addressed earlier and they include, among others, underspecification of the data collected, or lack of hard data needed to statistically predict unwanted events. In addition, datasets are often categorised for ease of interpretation, and this can mask cross-boundary effects, and measurement tends to be safety-area specific instead of holistic. A good example here is the Überlingen mid-air collision, and the follow-on investigations that uncovered many organisational and industry contributions that created the conditions under which the collision was possible, in addition to actions directly involved in the collision (Johnson, 2002). Yet, as discussed earlier, the faint signals of drifting into failure are usually, if not always, present, and we need robust measurement techniques that can capture these signals prior to disaster. Unfortunately, capturing signals requires the use of soft data collection techniques through activation of the human element. Some of these techniques are in place but either lag too far behind actual operations, or are either resisted or ignored due to organisational pressures.

An important part of the resilience movement from a risk perspective is to shift the focus from what goes wrong, usually in the form of undesired events, to how and why things go right in a complex and evolving environment. It is the shift in mindset at both the leadership and operational levels that will actively engage the human element in a more proactive manner that will improve SMS effectiveness. But the soft data is often difficult to quantify, and sometimes it is difficult for leaders to make safety changes prior to something actually happening. This does not mean that hard statistics are of no value, but that we need to complement hard data with soft data techniques to improve SMS effectiveness. Capturing the signals of drift include non-traditional metrics such as individual observations and personal interpretations of evolving operational situations that often diverge from expected norms, and even conflict with prescribed operational rules, regulations, and procedures. Capturing and reacting to these signals in a timely manner could improve operational effectiveness and avert potential disaster. The Columbia space shuttle disaster is a good example of failing to interpret and react to the signals that were present. So the point is, we need better metrics to capture the faint signals of organisational drift, real-time, and the ability to interpret and communicate these signals to those in the organisation/industry that can act. And then, action needs to be taken.

So the real question is what to measure, and how often? In addition to current metrics, there are two areas, in particular, that can improve the measurement of effectiveness in SMSs. First, modern SMSs routinely conduct safety climate surveys to measure the pulse of the organisation. These surveys are attempts to quantify qualitative safety characteristics within an organisation. But these surveys are not real-time, and only give a limited "snapshot" of reality at one given point in time in a specific context. And these snapshots are only as good as the quality of their design, and how the information is used afterwards. Even so, they rarely capture the entire organisation but will vary across divisions within an organisation, and across boundaries within industries. So their value is limited though still an important tool, if used properly. One way to improve the value of these surveys is to increase their frequency, and add measures of resilience from the Human Resources Management field. Also, if not already a part of the surveys, add a qualitative section within these surveys that address resilience specifically.

The second area of measurement improvement needs to be made in how reporting systems function in SMSs. At face value, this sounds like an easy fix, but it is not. This will involve structural, organisational and individual (psychological) changes both within the organisation and within the industry. This paper has suggested that by building resilience into an organisation, individuals will better capture signals of drifting into failure and will be more willing to pass that information on to those that can act. But detection alone is not enough, the information has to be exploited by the organisation, and adaptation needs to take place prior to crossing operational boundaries. This will encourage more frequent feedback, even continuous feedback between varous levels within an organisation, and to external stakeholders.

5. Discussion

In this paper, I have examined the current state of safety and safety management systems (SMS) in the transport sector using a Resilience Engineering lens as a basis for further discussion for potential improvements. As demonstrated in the presentations above, each of the different transport sectors addressed in this paper (aviation, maritime, rail, and road) have different histories, different technological and economic challenges, and different mixes of human-machine interface across several levels of interaction. In addition, each stuggles with different levels of environmental complexity related to societal demands for safety, history, governmental intervention, and control through regulation, economic pressures, technology integration issues, and the introduction of new types of transport vehicles. In effect, I have shown that we are not really dealing with finite systems, but what Woods (2016) calls Tangled Layered Networks (TLN) of Interdependent Units. This makes establishing and managing SMSs much more challenging.

We have also seen that despite significant improvements in safety performance over the years in most of the transport sectors through the implementation of safety management systems, there is still room for improvement. There is also great variety in the structural design and levels of SMS performance across the different transport sectors. Implementation and use of SMSs also vary across national boundaries, and even within organisations. This is understandable considering the varied nature of each transport sector and the socio-technical diversity found in each. One factor common to all SMSs is the traditional focus on statistical analysis of incidents as a means of predicting future events gathered through subjective statistical reporting systems that vary across industries, and even within industries. Some industries still focus on linear interactions instead of taking a systems approach to accidents, and is particularly true in the road transport system (Dekker, 2012). As we approach "ultra safe" levels of performance, these statistics, particularly those that do not focus on the system as a whole, no longer give us the capability to predict future undesired events with any accuracy, and we often meet surprise, and are consequently forced into "jousting with dragons."

As a response to this situation, I have proposed incorporating a new approach to risk management into current SMSs known as Resilience Engineering that designs the quality of resilience into the structural, social, and individual (psychological) levels of an organisation. This new systems approach to risk management does not replace current SMSs but, instead, addresses the inherent weaknesses of current structures and processes, and considers a shift in focus from traditional reactive measures (see Figure 2) that are less useful and effective, to interactive measures through promoting individual engagement in the form of individual sensemaking and mindfulness (Weick and Suttcliffe, 2006). However, shifting the burden of detecting impending failure onto the operators requires new approaches to managing SMSs, and incorporating soft-metrics in the form of noticing and reporting during operations. These soft metrics can also be included into current safety culture surveys.

Modern safety management systems perform two functions. The first is to demonstrate to external and internal stakeholders that safety is a priority and taken seriously. The second function is managing risk at all levels to reduce the occurance of undesired events, or to reduce the negative impact of undesired events when they occur. We have seen that we can no longer afford to improve safety performance through "trial-and-error" learning, and that looking backward after an undesired event, though important, often leads to the next event (Safety I). Instead, we need to shift our focus on to what goes right, and engage the unique adaptive capabilities of the "man-in-the-loop" (Safety II). But here we have a problem. Traditional control-based systems, consisting of rules, regulations, routines, procedures, and strict compliance demands, are not suited for complex, dynamic-adaptive systems experiencing continual change. The traditional metrics of statistical analysis of undesired events are no longer useful in predicting the next event. And we have shown that rules and routines are often created within organisations to satisfy external stakeholders creating different levels of understanding within organisations, and different rule compliance (Lofquist, Dyson and Trønnes, 2016). And this often leads to non-compliance. However, as we have seen, compliance is not always desirable since rules and routines are not capable of managing dynamic systems, and this is clear at the operator level.

Creating resilience in the transport sector requires a broad knowledge and understanding of the nature of complex, dynamic-adaptive socio-technical systems at all levels - both internal and external. But in particular, this needs to be embraced by the leadership and used to change safety behaviour. As we have seen, each of the different transport sectors have vastly different external environments with different both social and physical challenges. The socio-technical balance in each transport sector is unique, continually changing, and differs from country to country. We have also seen that the amount, and effect, of the governing regulatory structures are different, and have different levels of influence on safety performance. Despite concerted efforts to improve safety performance in each of the transport sectors, undesired events still occur with varying levels of consequence.

The traditional paradigm of "safety by design" needs to be challenged, and this is supported by Maurino (2017). Yes, systems are designed with the best intentions for safe results, but history shows that unexpected failures still occur. And, as pointed out by Perrow (1984), undesired events are just normal outcomes allowed by the system as designed, though undesired, and usually unexpected. So we cannot expect that systems design considers all likely outcomes, or that the system will not evolve over time. Instead, we must understand that modern transport systems are complex, dynamic-adaptive systems where people should be considered as an asset to safety. We have seen that safety management systems in-place have had a positive affect on safety performance, but each transport sector faces different challenges. This focus on change has been the main focus of the Resilience Engineering paradigm since its inception.

The first area to focus upon should be on educating the leadership at all levels on what actions can produce positive effects on safety performance. I have called these resilient behaviours. This will also clarify the leadership's role in managing safety management systems. Maurino (2017) points out that a performing SMS must seamlessly integrate safety management processes and institutional arrangements. This includes both leaders within organisations, as well as external stakeholders that have influence within organisations (society, governments, regulators, etc.).

Leaders must understand the concept of complex, dynamic-adaptive systems, and that outcomes cannot be controlled through static rules, routines, regulations and compliance, alone. Strict compliance regimes stifle sensemaking and mindfulness, reduce organisational commitment, and create situations where operators feel that their hands are tied, and that adaptation is not allowed. Rigid rule following also reduces the need to think, and interferes with noticing the weak signals of systems evolving into failure, leading to surprise. This surprise comes not only at the individual level, but for the entire organisation.

Empowering operators through knowledge and organisational support is a good start. Wilson and Ferch (2005) argued that we can only achieve the levels of resilience desired by reducing the reliance on compliance-based procedures, and to create caring relationships. By developing caring relationships, both between leaders and followers, and between individuals within units at all levels, we can promote resilient behaviours through psychological constructs, such as: autonomy, participation, self-efficacy, organisational commitment, task ownership, job-satisfaction, belonging, and mindfulness. These are constructs already measured in the Human Resource Management field, and should be included into safety surveys.

The second area of improvement is to build resilience into the supporting technical structure allowing operators more time to adapt to systems drifing into disaster, and better signals of impending surprise. This what Woods (2016) described as graceful extensibility. This requires better understanding of where boundaries are located and how to avoid crossing them. However, this is not easy as these boundries are continuously moving over time. One added benefit of understanding boundaries is that top performance and best economic return often comes from operating near the boundries where others are not able to operate. This allows adapting processes before surprise, but it also requires anticipation. Anticipation is a part of mindfulness – the process of noticing and understanding what is going around you in anticipation of something going wrong. As mentioned above, compliance-based regimes expect rules to be followed, and this is often in opposition to being attentive and anticipating impending failure. This requires continual improvement in technology and learning programs to keep operators updated and competent, as well as creating local ownership of one's tasks and the autonomy to deviate when required.

The third area of improvement is to create a supportive safety culture that promotes resilient behaviour. As discussed earlier, culture cannot be managed precisely, but it can be influenced. But this influence may have different effects across different levels within an organisation. Leaders must understand that they cannot dictate culture, but instead leaders need to communicate the desired culture and create the environment that allows individuals to experience this desired culture firsthand. Through this experience, culture will evolve toward the desired culture. But to create a resilient environment to support such a culture change needs deliberate actions by the leadership. First, to achieve a desired culture, leaders need to link the desired culture to the organisational strategy, and the chosen direction of the organisation. This includes establishing clear organisational values and how the organisation will achieve its goals. Next leaders need to introduce defendible goals that are realistic. This strategy then needs to be communicated, understood and accepted at all levels within the organisation. And finally, this message needs to be consistently communicated over time, often years, to achieve real change. In some instances, real culture change will require an entire generation shift.

6. Conclusion

In this paper, I have introduced a new perspective for improving safety performance in Safety Management Systems based on the field of Resilience Engineering. The intention is to create

resilient organisational behaviour through structural, social, and psychological changes that both engineer resilience into organisational structure, both internal and external, and promotes resilient behaviour by individuals at the sharp end of high-risk operations.

But I have also indicated that to do this, something has to change. We have to shift our focus from how things go wrong (Safety I), to how, and why, things go right (Safety II). It also requires a deliberate shift away from a culture of strict compliance to a culture of mindful adaptation. This change is needed to move away from behaviour control through static rules and regulations, to the promotion of adaptive behaviours that anticipate drift into surprise, and allow for timely, local adaptation. This ability to sense the Dragons prior to encountering them, and changing directions to avoid jousting with them, is the key to resilient performance.

I have highlighted the importance of leadership in changing this process, not just as a guiding structure (noun), but as a way to promote resilient behaviour through relationships and actions to create a supportive culture. However, changing culture is not an easy task. Most attempts at cultural change fail, or at least fail to reach the level of change desired. This is often due to a lack of clarity and agreement of the desired culture, or a lack of continuity of actions. Or even that the actions do not reflect the reality of real operations. As culture changes through interaction with the environment, it is a living process and needs continuous attention, and adjustment by the leadership.

And finally, we need to incorporate soft metrics into Safety Management Systems that complement hard statistics. But this will not happen unless the other changes discussed in this paper are met. We also need to increase the frequency of soft metric collection, even approaching continuous collection. This will require rethinking how we collect safety climate data. In particular, we need to find a real-time process that engages individuals and helps them to capture signals of drift into failure. This is a key characteristic of resilience. In addition, we also need reporting systems that allow individuals to translate these signals into action at all levels within an organisation. Adopting psychological constructs from the HRM field into safety surveys, such as: autonomy, self-efficacy, organisational commitment, social capital, belonging, and job satisfaction, can be used to measure the effects of leadership actions on resilient behaviour. Although these are lagging indicators, they will at least give a better view of the state of the organisational culture that can be understood more fully through other qualitative means, such as semi-structured interviews based on the findings of safety surveys.

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