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Systems thinking in transport safety

Cross Modal Safety Change Programme

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Foreword

This document has been written in three parts. The first seeks to answer the question “How can I use systems thinking to make transport safer?” The first part has been written in a discursive style and is intended to introduce transport professionals to “systems thinking” and the core concepts that characterise this approach. This part of the document is intended to challenge readers to consider their own approaches to problem-solving and uses a series of examples, both fictitious and real, to highlight how systems thinking can be used to analyse and solve transport safety problems, and to show where a lack of systems thinking can increase risk.

The second part of the document presents a review of systems thinking tools that are currently used in the transport sector. This part of the document is intentionally more formal than the first and should be treated as a reference guide to the tools available to systems thinkers. In the second part we provide examples from literature where systems thinking tools have been applied in the transport sector and encourage readers to use these references as a starting point to incorporate systems thinking into their professional practice.

Throughout the first part of the document we have provided links to the relevant tools at the end of each section. Readers may wish to study the examples given as they go along, or refer back to these having finished reading the first part of the document.

The third part of the document provides:

- A summary – how systems thinking can be applied to improve transport safety.
- Conclusions – the fragmented approach and different tools that are used to improve safety across the transport sector today.
- Recommendations – the key take-away is that systems thinking has far more to do with the mindset you have when approaching a problem than the tools that can be used when solving it.

Executive summary

This document was prepared for the UK Department for Transport, by TRL, as an introductory guide to the application of systems thinking to transport safety. The document is separated into three parts. The first uses a series of case studies from road, rail, air and maritime transport to illustrate the key concepts and theories of systems thinking. The second is a review of systems thinking tools that have been used in the transport sector, with examples from literature, and is a foundation for further reading and research. The third provides conclusions and recommendations for consideration when choosing systems thinking tools and applying the systems thinking method.

Introduction – what is systems thinking?

Systems thinking is a discipline that seeks to analyse situations and solve problems by developing a holistic understanding of the structure of a system and the agents and actions that are influencing its behaviour. The “system” can be any interconnected set of elements coherently organised in a way that achieves something, whether deliberately or otherwise. Thus, a system could be a machine, like a bicycle or a petrol pump, but could also be a less tangible thing like a bus service, which incorporates machines (buses), physical infrastructure (bus stations, shelters, etc.), humans (bus drivers, bus passengers, bus company managers, etc.), and information and procedures (timetables, routes, driver rotas, etc.). The constituent parts of a bus service, many of which are acted on by agents and influences external to the bus service itself, are still part of the system in which the bus service operates. Examples of these include road characteristics, other road users, weather, the locations and working hours of major employers of bus passengers, and the income available to passengers to pay bus fares.

Systems behave in ways that are different to the sum of the behaviour of their individual parts. The fundamental difference between systems thinking and more traditional, reductionist, scientific methods is that systems thinkers seek to build a holistic understanding of the ways in which the elements within systems interact to influence the behaviour of the whole. More traditional reductionist methods seek to isolate individual elements in order to determine their intrinsic properties, while systems thinkers seek to analyse multiple elements in order to understand the system as a whole.

Part one – case studies to illustrate key concepts

In Chapter 1 we offer the example of a fence and a gate, which when considered in isolation have fundamentally different behaviours to a system composed of both a fence and a gate working together. In later chapters we use the examples of the capsize of the *Herald of Free Enterprise* and the crash of Air France flight 447 to illustrate how the interactions between “machines”, the humans who operate them and the social structures that influence those humans must be considered as a holistic system to properly understand how safety can be improved. In both cases the mechanisms of the machines functioned largely as intended, but failing to consider how those machines interacted with very non-mechanistic human behaviour and social structures led to tragic accidents, which killed hundreds of people.

Feedback is a key concept in systems thinking. In Chapter 2 we discuss feedback loops in both the mechanistic sense (i.e., how they might be used in a machine) and in the much broader sense in which the investigation of incidents can be used to improve safety. We highlight the risk of complacency when events become routine, both in an operational sense (e.g., the regular, incident-free departure of a ferry) and in an emotional sense (e.g., the daily toll of deaths and serious injuries on the roads, which account for thousands of times the numbers of casualties in maritime, air or rail transport but which trigger little if any public outrage or governmental action).

One challenge for systems thinkers is determining where the boundaries of their systems lie. It may be tempting, and in some cases even useful, to analyse a very broad range of interactions – does the brand of tomatoes sold in the local supermarket somehow affect the number of people injured when using zebra crossings? In Chapter 3 we discuss the risk of failing to adequately consider the potential permeability of a system boundary. We illustrate this discussion using the example of the Selby rail crash, an accident in which two apparently separate systems interacted in a manner that had not been foreseen. We also highlight the growing challenge for transport agencies dealing with unprecedented, but increasingly frequent, disasters brought about by climate change.

One theme of Part 1 of this document is that the effects of interventions are often delayed, dependent on interaction with other interventions and behaviours, and cannot be measured in isolation. This is especially true for systemic interventions, such as policy changes, whose effects can often only be seen when viewed at a systemic level rather than when seeking to detect specific changes.

Another theme is those factors that go into creating a robust system; that is, a system that is resilient to failure even when elements and actions within it fail, and even if failure occurs can prevent the propagation of that failure and recover quickly. We provide several examples of adverse events that have occurred due to fragility in systems, which were thus susceptible to catastrophic consequences of minor mechanical or human lapses. We make the point that human frailty and error should be taken as a given, and that concentrating on penalising people for their shortcomings, at the expense of understanding how a system can be made more robust, is unlikely to yield positive safety outcomes in the long term.

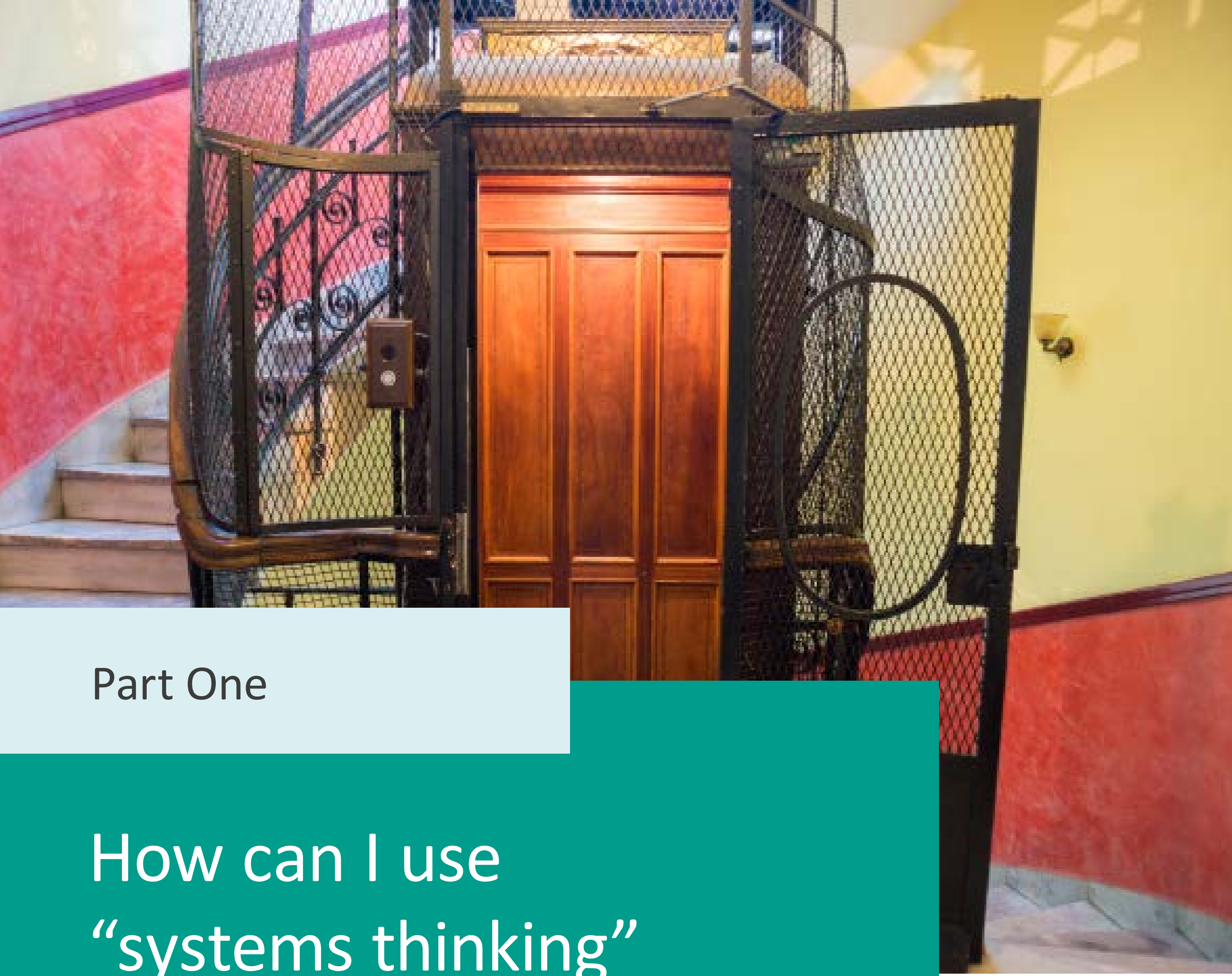
In Chapter 5 we discuss the emerging challenges of automated vehicles and the difficulty of creating robust systems to ensure that they can be operated in a safe, effective and equitable manner. Here we make the point that the interface, in the broadest sense, between the automated machine and the humans around it must be carefully designed and regulated to ensure that the risks of unintended consequences are minimised. While there are potentially significant safety benefits to be derived from systems that eliminate the variability which is inevitable with human operators, the risks, and potential consequences, of automated systems failing are very significant. Those systems must consequently be subject to robust regulation and organisational systems to ensure that minor failures cannot propagate into disasters. Automated systems need not be designed with malign intent to have catastrophic effects – we must always be sure that humans remain in control of those systems.

Part two – tools

A wide range of tools and techniques have been developed to support systems thinkers, ranging in complexity from very simple methods for representing systems in diagrammatic form, to complex theoretical frameworks for analysing the interconnections within socio-technical systems. In Part 2 of this document, we provide a review of a selection of those tools. We have divided these tools into two groups, which we have called "Systems thinking approaches and methodologies" and "Communication tools used in systems thinking", which broadly indicates whether those tools embody a sophisticated philosophical framework for thinking about systems or are more simplistic techniques that may be applied in combination with those more sophisticated methods. We provide details of 22 different tools. This is not an exhaustive list of the tools that could be applied to systems thinking in transport safety, but it is intended to act as a primer for practitioners who are new to systems thinking. It is also important to stress that systems thinking is not primarily a tool-driven discipline; just because you are using a systems thinking tool doesn't mean you are doing systems thinking. Conversely, it is possible to be a systems thinker without any knowledge or use of systems thinking tools.

Part 3 – conclusions and recommendations

In Part 3 of this document, we provide some recommendations and conclusions on the use of systems thinking in transport safety. Here we reflect on some of the philosophical principles that have developed within the systems thinking discipline. We discuss the idea that "problems" and "solutions" may be considered to be subjective constructs that exist only from the perspective of certain viewers.



Part One

How can I use "systems thinking" to make transport safer?

1 Introduction – what is systems thinking?

1.1 What is a system?

Donella Meadows defined a system as "an interconnected set of elements that is coherently organised in a way that achieves something". Systems behave in a way that is different to the way each of its parts behave independently, so a gate by itself and a fence by itself will behave in a completely different way to a fence and a gate acting together as a system. If you place a gate in the middle of a field full of sheep then, apart from acting as a convenient scratching post, it won't have any effect on the lives of the sheep. If you build a fence through the middle of the field and confine all the sheep to one side then you might have a huge effect on the day-to-day lives of the sheep – preventing them from accessing the lusher grass or the best shelter in a permanent way. But if you put a gate in the middle of the fence then suddenly you create a whole range of new potential system behaviours – when the gate is open the sheep can move freely from one half of the field to the other; when the gate is closed the sheep can be confined to one side or the other of the field. One group of sheep can be separated from another by letting some sheep through the gate but not others. The farmer can close the gate to let the grass grow in one half of the field while the other is grazed, before herding the sheep though the gate to graze the other side, so the sheep never run out of food, and so on. None of these behaviours are possible with a gate or a fence alone; only the system of gate and fence working together make these behaviours possible. Equally, if the gate was placed by itself, separate from the fence, in another part of the field, the system would lose its function.

1.2 Reductionism – the opposite of systems thinking?

When the scientific revolution came to Europe in the seventeenth century, one of the key changes it introduced was reductionism. Reductionism seeks to explain all phenomena in terms of their most fundamental parts. In chemistry and physics this led to an ever deeper analysis of the fundamental composition and structures of matter – leading to the discovery that “air” was actually a mixture of gases, and that those gases were composed of atoms, and that those atoms were composed of protons, neutrons and electrons, and that they in turn were composed of quarks and gluons, and so on. Before the scientific revolution, alchemists put a lot of effort into trying to turn base metals into gold – and failing. Modern chemistry has shown us exactly how to turn lead into gold – you simply remove three protons from the core of each lead atom. But systems thinking should encourage you to think about the cost of removing those protons and the relationship between the amount of gold in the world and its monetary value, which will help you to realise that alchemy probably wasn’t a great idea in the first place.

Reductionism is a key tool in the scientific method as it allows us to cut out all of the “noise” that obscures what’s really going on. When we design an experiment, we usually do it in a highly reductionist way – eliminating any “confounding variables” that might cause us to make misleading observations. But reductionism might lead you to think that the best way to test agricultural infrastructure is building gates in the middle of fields to isolate their effects from those of fences, and leave you wondering why the sheep just ignored your experiment. That doesn’t mean that reductionism is wrong and should be discarded; it simply means that complex problems that result from the interaction of multiple elements and interconnections are not best solved using traditional reductionist methods.

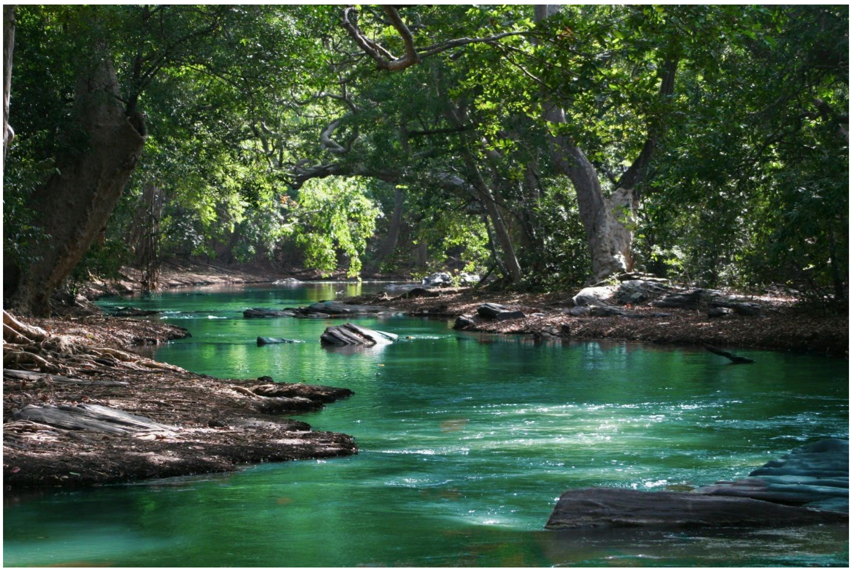
The reductionist scientific method almost always works on the basis of finding the average result for the average set of conditions. Anybody who ever measured the number of bubbles produced by a piece of Canadian pondweed in a year nine biology experiment knows that you have to take at least three measurements, add them together and divide by three to get the “real” answer. But that piece of pondweed that produced ten bubbles really did produce those bubbles, just as the one that produced a hundred did!

Systems thinking seeks to understand what’s going on at a macro level and focuses on the interactions between different elements of a system that give it its properties. When applied to mechanical or electronic systems, systems thinking allows us to define a precise set of equations that predicts the behaviour of the system based on the function of each of its constituent parts. But when we apply systems thinking to problems that involve people and pondweed, things can get a lot more woolly.

The big problem with people, and many other very complex systems, is that they don’t behave in a deterministic way – they don’t behave the same way every time they get the same inputs. While many mechanical and electronic systems are almost completely deterministic – press the button and the light comes on – complex systems, like those involving people and pondweed, are not. So, it’s important to understand that it may not always be possible to reliably predict the precise behaviours of complex systems, but understanding the relationships that exist within those systems will help to make our predictions more likely to be accurate and reflect the range of potential outcomes.

1.3 Understanding problems by thinking about systems

Stoke Pewsey has a problem. This year there have been six collisions involving pedestrians. So far none have been fatal but there is serious concern among the community, police and town council that it is only a matter of time before a fatal incident occurs. Various measures have already been put in place to try to reduce the number of collisions, including more speed enforcement, a new pelican crossing and traffic-calming measures in the town centre, but collisions keep happening. How could a systems thinking approach help to improve road safety?



For thousands of years Stoke Pewsey was just a shallow spot in the river – the only safe place for five miles where people could wade across to get to the other side of the valley. That natural anomaly funnelled people and animals from miles around into one spot. Over aeons that spot, left there by the last ice age, became the best place to swap berries and nuts for flints or furs and more people gravitated there. Eventually, somebody built a hut – a crude affair of mud and sticks to keep the goods they were trading dry and secure. In a generation, that hut became two huts, three, four, shelters for living and trading, places to sell food, ale, pots and blades. The trackway to the river, compacted over millennia by feet and hooves, grew wider, and muddier, as farms sprang up and farmers began driving their flocks and carts to the crossing. When the Normans arrived, they built a bridge, first in wood, then stone. Eight centuries ago a Plantagenet king issued a charter for a market to be held, formalising in vellum and seal what had been growing organically for a hundred centuries, and it's been there ever since. Nobody planned Stoke Pewsey. It just grew there, at the shallow spot in the river, driven by the topography of the valley and the behaviour of the people who lived in and travelled through it.

Mud and thatch gave way to stone, brick and concrete, a roadside temple came and went, a church rising in its place. Where once people met to swap flints for food now Greggs and Costa stand. The trackway to the river reached its limit and for the first time in ten thousand years a new crossing place was found, this time spanning the valley in steel and concrete. But the needs of the people didn't change – a place to cross the river, some shelter to live and trade. Soon the new bridge drew people to a new trading spot, outside the town, more easily reached by trucks and cars. The logic was sound: a wide, flat site, easily accessible from the new bypass, carefully designed to support the flow of traffic. Large, steel-framed, rectangular buildings sprang up – shelter for factories, supermarkets and cinema.

1.4 What's in our system?

Viewed from a system perspective, Stoke Pewsey originally had a single function – a safe place to cross the river. That function gave rise to some emergent properties – meeting place, trading place, junction between trackways. Over time these developed into functions of their own – people travelled to Stoke Pewsey (or at least the spot on the riverbank where Stoke Pewsey would eventually stand) for the sole purpose of trading, with no intention of crossing the river. As time went on, the relative importance of the functions changed, and new ones were added – shelter to live and work, education, worship, and so on – but the original function, as a place to cross the river, persisted. In the UK, most towns and cities developed in this way, evolving slowly in response to topography and human behaviour, having arisen usually from some natural phenomenon in the landscape – a shallow spot in a river, an easily defendable hill, the mouth of an estuary. While in ancient times there may have been some planning and design, usually associated with making places defendable against attack from outside, much of the process of urban development was purely organic and evolutionary – following the path of least resistance (literally) as people sought easy routes from one place to another and easy places to erect shelters.

In modern times that process of organic evolution has been replaced by a much more deliberate process of planning and design, and it has been subject to significant disruptive influences as new transport modes were introduced. Canals, railways and finally internal combustion engines have all had enormously disruptive effects on systems that had been evolving slowly around a single transport paradigm for millennia. The construction of new transport hubs such as railway stations or car parks, and new centres of activity such as shopping centres, factories and football stadia, has shifted the focal point of many towns and produced new, or reversed old, directions of flow between places.

1.5 Time to talk about bathtubs!

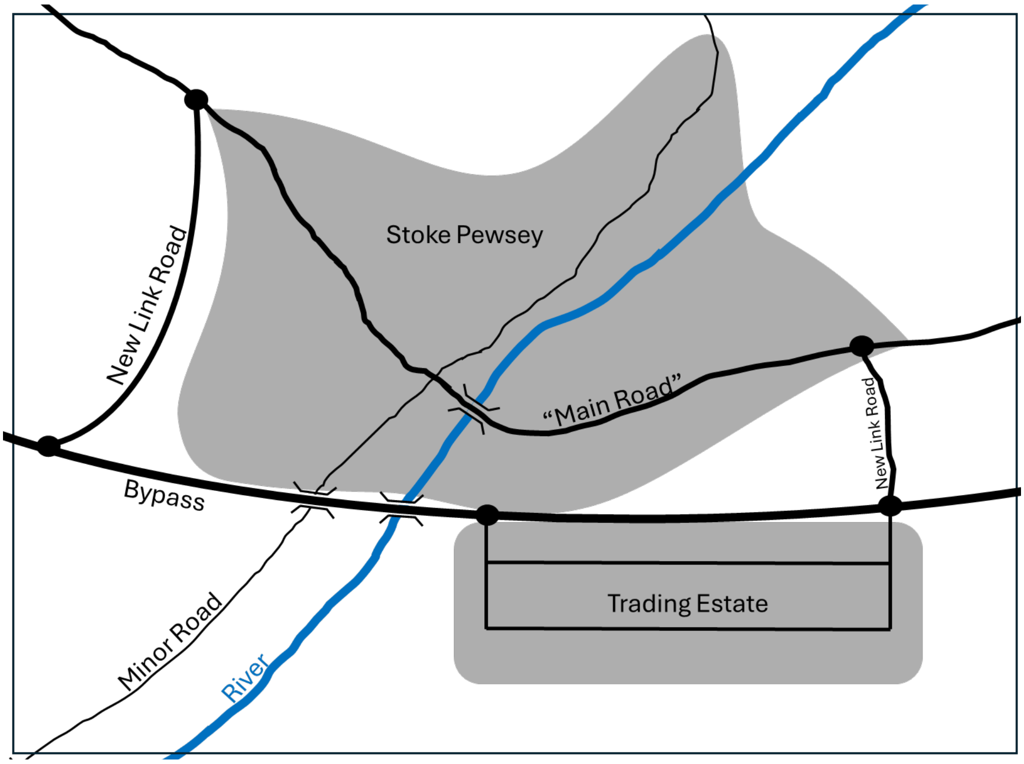
Systems thinkers have an unhealthy obsession with bathtubs, so let's keep this brief. An important concept in systems thinking is that of "stocks and flows". In the bathtub analogy, the stock is the water in the bath, and the flows are the water coming into the bath from the taps and the water leaving the bath down the plughole. If we want to increase the level of water in the bath (people in the town, money in the economy, fruit in the supermarket) we turn on the taps (have more trains terminate in the town, encourage banks to give out more loans, charter a ship to deliver more oranges), and if we want to reduce the level of water in the bath we pull out the plug (offer cheap single tickets to another town, encourage investment in foreign companies, offer buy-one-get-one-free deals on oranges). At this point the analogy feels a little tenuous, but bear with us.

The original Stoke Pewsey system was all about flow, with no emphasis at all on stock. People went to the spot in the river where they knew they could cross, crossed and left again. As the function of that spot in the landscape started to evolve, stocks started to become more important. In order for a meeting to occur it was essential that there was more than one person in the system at a time. If you wanted to trade, it made sense to make yourself into a stock – by hanging around on the riverbank until somebody else came to cross, whereupon you could swap some nuts for a fur or other goods. As the primary function of the system moved from crossing the river to trading, more people deliberately made themselves into stocks (of potential traders) by deliberately waiting on the riverbank. Now the flows and stocks of people were joined by flows and stocks of goods to be traded – nuts and berries came in, flints or furs went out, so if anybody ever visited there was likely to be a reasonable stock of all four available for consumption when required. Very few of the goods traded arose at the spot on the riverbank where they were traded, so everything that came out at some stage had to have come in, although of course not everything that came in had to come out again – many of the nuts and berries never left, at least not in the form they had arrived.

Many systems, if they aren't excessively constrained, will self-optimise over time. We've all seen desire lines – paths created by walkers as they cut a corner. Towns happen when you allow desire lines to develop for ten thousand years – "I could build my shop in the middle of the forest where nobody ever passes, but it would make much more sense to build it next to the other shops that are already there". The reason we have high streets is because somebody built their shop next door to another shop, and then somebody else built a shop next door to that, all along the road where most people were travelling already – an emergent property of the simple desire to maximise the number of interactions that could potentially lead to a trade being made.

1.6 A tool to help understand the system

Below is a systems diagram to help illustrate how the transport safety problem in Stoke Pewsey might have arisen. We wouldn't usually call it that of course; we'd usually call this a map, but it is, in essence, a visual representation of a system, which happens to be a physical place. The diagram allows us to quickly understand the relationships between different parts of the system, in this case the river, the roads (old and new), the places where people live in the old town and the places where people might want to meet to trade, work and socialise in the new trading estate. By looking at this diagram you might already be getting a hunch about why the town has developed a pedestrian safety problem, and why previous attempts to address it have been ineffective.



In this case the roads provide a proxy for the flows of people and goods around and through the system. The outline of the old town shows where the stock of people is most likely to be found, and the trading estate shows where the greatest stock of goods and other trading opportunities will be. For most of the history of the town, people would have flowed east to west along the trackway that eventually became the main road, or north to south along the minor road that follows the course of the river up the valley, which in ancient times was just a path from one crossing place to the next. When the bypass was built, the primary flow of east to west traffic moved away from the town, the old main road becoming the taps and plughole for people whose primary purpose was visiting the town rather than travelling further afield. The new trading estate was positioned to take advantage of that new flow of east to west traffic. Traffic flow between the old town and the trading estate is catered for by link roads between the old main road and the new bypass at the original entry and exit points of the old town.

But now consider the flow of pedestrians. The basic layout of the old town is the result of ten millennia of pedestrian desire lines augmented by fifty years of modern planned development. To a significant extent the living and trading functions of the town are collocated in the town centre. The town has grown by expanding outwards from the original crossing point. In later years, like most towns, that growth has been in purpose-built housing estates whose road networks are deliberately self-contained – the only flow being into and out of the estate. The flows of pedestrians and vehicles alike are channelled onto the original road network. Before the construction of the trading estate nobody entered or exited the town on foot, and the concentration of pedestrian traffic reduced rapidly from the town centre to the outskirts of the town.

But now that the trading estate is open, how should a teenager wishing to spend an evening at the cinema, or a worker without a car going to work at a factory, make their way from their homes in the north of the town to the trading estate? From their perspective, far from being a flow path, the new bypass is actually a barrier, just like the river. The river forces them into the town centre, since that is the only crossing point available to them, but from there their only route is to follow the main road to the east and then the new link road south. These roads on the edge of town, which previously saw little if any pedestrian traffic, have now become a primary pedestrian route.

1.7 Asking questions about the system

One of the big worries for new systems thinkers is that they don't know about every element and interconnection in the system. But systems thinking doesn't depend on omniscient knowledge. Instead, systems thinkers need to learn to ask questions about the system and explore the levers that can be used to influence the system to move towards the desired outcomes.

So why haven't the interventions made to reduce casualties in Stoke Pewsey worked? The first question to ask is how are we so sure that the measures put in place haven't worked, or won't work in the future? We don't know for sure that there wouldn't have been 12 incidents if the initial interventions hadn't been made. It's unlikely in most cases that there will be a single magic bullet that will eliminate the problem completely. Measures such as speed enforcement are essential in ensuring that a system functions as we designed it; for example, that where we put in our 40mph speed limit, drivers are actually driving below that speed. But we have to ask first whether the speed limit is appropriate for this road – the way it's being used now, the way it was designed, it's width, it's lighting, the facilities it has for pedestrians, the number of pedestrians and cyclists who are using it, the time of day they are using it most.

Many of the changes we make will take time to have an effect on the outputs we're interested in. Humans have a significant amount of "behavioural inertia", which is why they've been crossing the river in the same spot for ten thousand years in the first place. It will take time for people to engage with some of the changes you make – to change the routes they use to take advantage of a new pelican crossing. And sometimes those interventions will only work in combination with other interventions, so the pelican crossing might be more effective if it takes people towards the new pedestrian path being built from the town centre to the trading estate, but only **after** the path is built and only after people get used to using that route.

It's important to remember that many interventions are effective on average, but they may not be effective for the specific problem you're trying to resolve. So, traffic calming, speed enforcement or pelican crossings might on average reduce the number of incidents on roads where they are applied, but that doesn't mean they will always be effective on a particular road. In the same way that taking a paracetamol once a week will reduce the average number of headaches suffered by the group tested but won't cure **your** headache unless you take it that day.

Key messages

- A system behaves in a way that is different to the way each of its parts behave independently.
- The reductionist scientific method will find the average result for the average set of conditions.
- Graphical tools can help explain how a system operates.
- The effect of interventions is often delayed, and often dependent on interaction with other factors.

Related systems thinking tools

Soft Systems Methodology (SSM): Visualise road safety dynamics (e.g., schools and crossings) using Rich Pictures (Section 8.2.1).

Boundary Judgements: Identify essential system elements like infrastructure and pedestrians (Section 8.2.3).

Multiple Cause Diagrams: Map interrelations (e.g., time pressures and road design) contributing to collisions (Section 8.3.5).

Rich Pictures: Capture the problem context informally to highlight system interactions (Section 8.3.6).

2 Feedback loops big and small – learning from disasters

Water began pouring onto the car deck through the open bow doors. Already ballasted low in the water to match the unusually low quayside at Zeebrugge, the speed of the ferry, as it accelerated towards the mouth of the harbour, sucked it lower still. Only 90 seconds after leaving the harbour, the *Herald of Free Enterprise* listed sharply to the left, recovered briefly and then rolled onto its side in the shallow water just beyond the harbour wall. By chance it came to rest just outside the deep channel into the harbour and lay half submerged in the dark water.

2.1 What is feedback?

Feedback is another core concept in systems thinking. There are some familiar examples of feedback in household systems – a thermostat that switches off the central heating when the room reaches the set temperature, or the ballcock in a toilet that stops the water when the cistern is full. Both are examples of negative feedback – the accumulation of the stock to a certain level (heat or water) triggers a signal to stop the flow into the system. Negative feedback systems are inherently stable since the feedback action always tends to reduce the flow and thus push the system back towards equilibrium. A positive feedback system is one in which the feedback action increases the flow into the system – imagine a thermostat that switches on another heater every time the temperature rises by five degrees. Such a system will never return to equilibrium unless it is acted on by some external influence – you switching off the power to the thermostat.

Legal controls are examples of negative feedback systems. If you drive above the speed limit, and get caught, then you are provided with some feedback in the form of a prosecution that is intended to dissuade you from doing it again – reducing the flow of speeding motorists. If you get caught speeding multiple times then your licence is revoked and, in theory at least, your ability to contribute to the stock of speeding motorists is removed altogether. The criminal law only ever operates in a negative mode – we are never sent a reward for obeying the speed limit. But legislation of other kinds often does operate in a positive mode, such as grants for installing solar panels or tax incentives for saving into a pension.

2.2 Feedback in machines

When lifts were first invented they had to be operated by an attendant, whose job it was to "drive" the lift, ensuring that the doors were closed before departure, releasing the brakes and controlling the speed and direction of the lifting motor to navigate towards the desired floor, carefully slowing the lift car as it neared its destination to ensure that its floor lined up with the floor in the lobby, and so on. The lift operator was a human control system, providing the feedback functions that the electrical and mechanical systems needed to work effectively.

Feedback systems are a key element of modern automated control systems, which are increasingly ubiquitous in transport systems of all kinds. Lift attendants are a thing of the past, and nowadays we entrust the operation of lifts to entirely untrained members of the public who have literally walked in off the street. We allow these “amateurs” to assume control of this complex machine because the machine itself is doing most of the decision-making. When you press a button in a lift you create a demand that starts the journey towards your desired floor. The first part of that journey is ensuring that the doors, both in the lift car itself and in the lobby, are closed – the control system sends power to the actuators that close the doors, and switches connected to the doors send a signal back to the control system to tell it that the doors are all closed and the next part of the journey can begin. If the doors either in the lift car or the lobby won’t close, maybe because your suitcase is in the way, then the control system will cycle the doors open–doors close sequence until a signal is received that all doors are closed and it’s safe for the lift to leave the floor. The control system then sends power to the main lifting motor, which raises or lowers the lift towards its destination until another switch, inside the lift shaft at the destination floor, provides a signal to tell the control system that the lift has arrived at the desired location. The control system then stops the main motor and applies the brakes.

From the perspective of the lift user, the process is seamless, but the control system of the lift has an intricate network of feedback loops, which ensures that the lift only ever behaves as it was intended to – never leaving a door open so an unwitting traveller plunges into the shaft, never carrying on past the desired floor and getting stuck in the basement, and so on. Without those feedback loops, the control system might send power to the door actuators, assume that the doors are closed and set off on its journey, without realising that half of your suitcase is still in the lobby.

2.3 Roll-on/roll-off

The roll-on/roll-off (RoRo) ferry is a simple concept, but one that revolutionised the transport of land vehicles by sea. The central design feature is a large open deck, close to the water line, with a ramp at each end. Vehicles can easily drive up one ramp onto the deck, park under their own power, in rows, like a floating car park, and then, when they reach their destination, simply drive out in the same direction they boarded, using the ramp at the far end of the deck. Before the invention of the RoRo, vehicles had to be lifted in and out of the holds of cargo ships by cranes, making the loading process slow and complex. But the simplicity of the RoRo ferry comes with a significant penalty to it seaworthiness. As countless documentaries on the *Titanic* constantly remind us, ships should be designed with watertight compartments so that, if water gets inside, it can be confined to one part of the ship and not compromise its buoyancy or stability. That single, undivided car deck that makes it so easy to load a RoRo ferry also makes it very difficult to contain and control any flooding. Worse, while sea-going ships are designed with strong prows to break through waves, RoRo ferries have forward-facing doors, close to the waterline, opening into that open car deck.

2.4 The fatal dangers of routines

In the moment it was a simple mistake. Like the final failure in so many catastrophic events, a moment of inattention, a simple omission compounded by a fatally flawed system that offered no defence against human frailty. Just like those original lifts, designed to be operated by a skilled attendant, the *Herald of Free Enterprise* was entirely dependent on its crew to provide the crucial feedback loops that ensured its safe operation. The assistant bosun was responsible for closing the bow doors. He was under the supervision of the chief officer, who should have checked that the task had been completed before leaving the car deck for his post on the bridge. The first simple omission was that the assistant bosun had gone for a break in his cabin and had fallen asleep. In a robust system this omission would not have been fatal, or even that significant – when the lift doors don't close, everybody shuffles about and the lift has another go, and nobody plunges into the open shaft or is cleaved in half by the departing lift. But the system on the *Herald of Free Enterprise* was not robust – it depended on the actions of one man. But there was a backup system to provide some level of robustness – the chief officer, whose job it was to supervise the assistant bosun. In subsequent testimony the chief officer claimed to have seen the assistant bosun heading for the controls to close the doors before he set off to his post on the bridge. He was of course mistaken.

It's reasonable to wonder why the chief officer didn't hang around to assure himself that the crucial task of making the ship watertight had been completed before leaving the car deck. But the chief officer found himself in the unfortunate position that he was required to be in two places at the same time – on the car deck to supervise the closing of the doors, and on the bridge helping the ship's master manoeuvre the ferry away from the dock. The assumption was that the assistant bosun would call the bridge if there was any problem closing the doors. But that assumption relied entirely on the assistant bosun being there in the first place.

In the subsequent enquiry there was significant criticism of the organisational structure at Townsend Thoresen, the owner of the ferry. The poorly designed organisational structure on board the vessel, which had given rise to the accident in the first place, reflected a lack of robustness that permeated the whole company. No individual had explicit responsibility for the safety of operations. A previous incident in which another of the company's ferries had left port with its bow doors open, without the catastrophic consequences that befell the *Herald of Free Enterprise*, had failed to set off any alarm bells, either literal or metaphorical in Townsend Thoresen's management. The company's ships' masters had requested that a system be fitted to allow them to check the status of the bow doors from the bridge, but this request had been denied. The masters could have implemented a system of positive reporting, requiring the crew to confirm that an action had been completed, rather than only reporting when a problem occurred. But there were five masters in the company, with none placed in a supervisory position where he could make decisions for the others. Thus, no decision was ever made, and no system was implemented.

Perhaps the greatest threat that had developed at Townsend Thoresen was that of complacency. Unlike the *Titanic*, this wasn't the *Herald of Free Enterprise*'s first voyage – it had been crossing the channel several times a day for seven years before that fateful night. They say familiarity breeds contempt, and that was certainly the case at Townsend Thoresen, where an absence of serious incidents had been mistaken for a reliable system. In light of the accident, the company's refusal to fit a system to confirm the status of the bow doors seems unbearably callous, but the day before the accident, with seven years of perfectly safe operation and an incident that showed that failing to close the bow doors wasn't a big deal anyway, the decision felt much less malignant. Likewise, the actions of the chief officer, under pressure to maintain sailing schedules and working with an assistant bosun who was known to be one of the best in the business, seems perfectly reasonable. Nobody set out to sink the ship, but the failure to implement robust feedback systems, both human and technological, meant that an accident was much more likely.

2.5 Learning from mistakes

What lessons should we take from the *Herald of Free Enterprise*? It's tempting to see this as a story of human frailty. Had the assistant bosun not fallen asleep then none of this would have happened. Often in road transport that is the conclusion we draw. People are regularly jailed for a moment's inattention – reaching for a mint or looking down at a text message. But that approach fails to acknowledge that we are all fallible – we have all driven home tired after a long day in the office, or upset by an argument with a partner, or been distracted by a fly on the dashboard or blue lights on the opposite carriageway. We must seek to design systems that are robust enough to cope with the unreliability of humans. But we must also consider the extent to which we are prepared to give up our freedoms in the service of safety. In Chapter 4 we'll see how the interplay between freedom and responsibility influences the design of regulations and think about the levers that can be pulled to exert a positive influence on systems to make them safer.

Sadly, 193 people died aboard the *Herald of Free Enterprise* – the worst peacetime maritime disaster to strike a British ship in more than a hundred years. The disaster led to fundamental changes in the design of RoRo ferries and the way they are operated, and no British ship has suffered such an accident since – indeed, it is included here as one of the few notable maritime disasters involving a British passenger ship in the last half century. But ten times that many people die every year on British roads with no public enquiry or fundamental changes to the system being proposed or made. We are perhaps too familiar with the dangers and too accepting of the risks that we take whenever we travel by road. The accidents and incidents that befall other modes are given huge significance because of their abnormality. Popular books, documentaries and blockbuster films are made about shipwrecks and plane crashes, but fatal road accidents rarely inspire more than a couple of paragraphs in the local paper.

Feedback is an essential component in a robust system. If we want to build robust transport systems then we must learn from the mistakes that occur within them, both human and technological. While it may be reasonable to seek to punish those who wilfully abuse the freedoms they enjoy, it is counterproductive to assume that human frailty can be litigated into compliance. Instead, we must seek to learn the lessons of each failure, and act on those lessons when we have an opportunity to do so. We run the risk here of being diverted into a discussion about our philosophy of responsibility, but no human system, no matter how well disciplined, can be infallible. Like our modern, attendant-free lifts, some of the solution may lie in the development of better technologies. Ones that take away some of the responsibility from the human traveller and automate the key steps necessary for a safe journey. We'll see in Chapter 5 that while technology has an important contribution to make to developing safe transport modes, the interaction with soft, human systems will always have a critical part to play in ensuring safety.

Key messages

- Feedback is a common feature of systems, both human and technological.
- Robust systems are designed to compensate for human frailty. Feedback is an essential component of a robust system.
- It is essential to balance the very human desire to punish those whose behaviour we condemn with the need to learn from their mistakes and understand how systematic failures arise.

Related systems thinking tools

Failure Modes and Effects Analysis (FMEA): To systematically identify the weaknesses in operational and organisational safety systems, such as reliance on human verification of bow door closure (Section 8.2.10).

Control Models: To depict feedback loops at operational and organisational levels, showing gaps in the systems that failed to prevent the disaster (Section 8.3.3).

Activity Sequence Diagrams: To map the sequence of operational steps leading to the disaster, highlighting critical points of failure and redundancies (Section 8.3.1).

System Dynamics: To illustrate how organisational complacency reinforced the risk of failure over time, creating a system prone to catastrophic outcomes (Section 8.2.12).

Rich Pictures: To visually represent the operational dynamics on the vessel, including crew roles, task sequences and the management structure, making complex relationships accessible (Section 8.3.6).

Conceptual Modelling: To contrast the flawed system with an ideal robust system that incorporates automated feedback and stronger procedural safeguards (Section 8.3.2).

Boundary Judgements: To analyse the scope of organisational versus individual responsibility, revealing gaps in the company's definition of safety accountability (Section 8.2.3).

Multiple Cause Diagrams: To trace how interconnected factors (e.g., human behaviour, operational pressures and technical limitations) combined to cause the disaster (Section 8.3.5).

Critical Systems Heuristics (CSH): To critique the organisational decisions and assumptions, such as prioritising efficiency over safety, and assess the alignment of values in system design (Section 8.2.4).

Causal Loop Diagrams: To visualise feedback loops in micromobility systems, illustrating the dynamic relationships between users, infrastructure and regulatory measures (Section 8.2.12).

Spray Diagramming: To map connections between stakeholders and key issues in micromobility regulation. Useful for brainstorming and identifying the complex interdependencies between user behaviours, safety concerns and industry standards (Section 8.3.8).

3 Unexpected interactions – understanding where the boundaries of a system lie

Systems thinking by its very nature seeks to take a holistic approach to the analysis and solution of problems. But in order to be a practical methodology, at some point you have to draw a boundary around your system. Occasionally you might be able to consider that boundary as a completely impermeable barrier that separates your system from anything else happening in the world. But more often we tend to think about system boundaries more like cell membranes – we know that there are things on the outside that might affect what happens on the inside, but the selectively permeable system boundary controls the type and magnitude of the effect they can have on what's going on inside the system and vice versa.

A good example of that selectively permeable system boundary is the level crossing. For the most part we can think of rail infrastructure as a completely independent phenomenon from road infrastructure. They might come close to each other, run along parallel routes or cross over each other using bridges or tunnels, but for the most part we can think of them as completely separate systems. One breach in that impermeable boundary is the level crossing. At a level crossing the road and rail systems can freely interact. At that point things that are part of the road system (e.g., vehicle type approval, driver licensing and speed limits) can all interact with things that are part of the rail system (e.g., signalling procedures, timetables, rail gauges). Some of those interactions (e.g., whether an express train has a buffet car or the reflectivity of road signs) might be of no significance whatsoever, but others (the frequency of train services on the line and congestion on the adjacent gyratory system, or the height of railway power cables and the maximum permitted height of heavy goods vehicles) certainly will.

Depending on what we are trying to achieve, we might take quite a reductionist approach and treat a single level crossing as a system in its own right – permeable in one direction to rail traffic and permeable in the other to road traffic. One question we might then ask is how do we ensure that the selective permeability of our system is selective in the right way? In other words, how do we stop the trains from ending up on the road and road vehicles from ending up on the railway? Actually, the answer to that first question is quite simple because the nature of railways means that trains are constrained to remain within their system, provided the system remains intact. As long as a rail or a train doesn't break, you don't need to worry about trains trying to wander off into other domains. But the second question is a bit harder. Because of their nature, vehicles and pedestrians in the road domain are not constrained to stay within the road system. It is entirely foreseeable that a car could enter a level crossing, make a hard right turn and set off along the railway. We might then want to introduce some additional controls to ensure that our system has two distinct states of permeability – permeable only to the railway when the level crossing is closed and permeable only to the road when the level crossing is open. Old-style, manually operated level crossings actually achieve this condition. When the gates are open to the road, they are closed to the railway and vice versa. It isn't possible to drive off the road onto the railway because the pathway through the system for road traffic is mutually exclusive to the pathway through the system for rail traffic – it is impossible for both pathways to exist at the same time.

Does that mean that this type of level crossing ensures separation between the rail domain and the road domain? No – because while the crossing is only permeable to one type of traffic at a time, it still brings together other properties of those two domains and causes them to interact. For example, the timetable that the railway is operating to, and hence the timing of when the crossing will be open or closed to road traffic, will affect congestion on the road that crosses the railway. If we view the crossing as a system in its own right, separate from the other systems to which it belongs, then we might fail to understand that the railway timetable could have an effect on the road network. Viewed purely from the perspective of the crossing there will only ever be two road vehicles waiting to cross when the gates are closed – one from each direction. The queues of traffic behind those vehicles don't exist if we consider the crossing as an isolated system. Nor indeed does the railway timetable – there either is a train approaching or there isn't. It may indeed be the case that operationally we actually want the crossing to behave as if there was no timetable – there's no point stopping the traffic for a train that's been delayed for 30 minutes, and we really must stop the traffic for a locomotive that has been sent back up the line to retrieve a broken-down express train. But from a traffic management perspective it makes more sense to model the crossing as part of the wider railway system and as part of the wider road network. That way we can better understand what effect a train crossing every ten minutes will have on road congestion and safety, compared with one every two hours. That might lead us to conclude that we need to build a bridge over the railway.

3.1 The danger of viewing systems in isolation

Viewing systems in isolation can be dangerous because by doing so we may ignore crucial interactions that could have serious implications for the safety of the systems concerned. Organisationally the rail network may be separate from the road network, except where the two cross. But in reality, the rail and road networks are not isolated from one another. In 2001 we were provided with a stark reminder that artificial system boundaries may not reflect reality.

At 06:13 on the morning of the 28th of February a Land Rover, pulling a trailer loaded with a car, left the westbound carriageway of the M62 and crashed down the embankment onto the main railway line between London and Newcastle. Uninjured, the driver attempted to reverse off the railway line. When his attempt failed, he dialled 999 to report the situation. This would have been a mildly inconvenient mishap, but for the fact that the 04:45 express

train from Newcastle was hurtling towards London at 125mph. The express train struck the Land Rover and trailer and was derailed, but remained upright. Though serious, this too might simply have been an inconvenient incident, were it not for one final, tragic coincidence. Travelling north was a freight train carrying coal to the power station at Eggborough. More than 600 metres after the initial collision with the Land Rover, the derailed express train was deflected into the path of the freight train by a set of points. Still travelling at almost 90mph, the express struck the freight train, which was travelling at 54mph in the opposite direction. The heavily built coal wagons tore through the much more lightly built passenger carriages, overturning most and sending them tumbling down the embankment. In total ten people were killed, including the drivers of both trains, and 82 more were injured. It is the worst rail crash in the UK in the 21st century.

3.2 So, what went wrong?

Just like the sinking of the *Herald of Free Enterprise*, the precipitating event was somebody falling asleep at a crucial moment. The driver of the Land Rover had allegedly not slept at all the night before the collision. He later claimed in court that a collision with something on the road had caused him to lose control and veer off the motorway. Ultimately, whatever the cause, the Land Rover and its trailer had left the road domain and entered the rail domain in a place where such an interaction was not intended to occur and for a reason that was trivial. The possibility that a vehicle could leave the motorway at that location had been considered, and mitigations had been put in place, but they failed to prevent the collision. A subsequent enquiry concluded that this was a once in 300 to 400 year event. The company that had insured the Land Rover paid out £30 million in compensation to the victims of the collision. They attempted to reduce their liability by claiming that in fact the Highways Agency (now National Highways) had been negligent in failing to erect a sufficiently long vehicle restraint system at the scene of the collision, but the court rejected this claim.

Is this another example of a fragile system? At a fundamental level the Selby rail crash and the sinking of the *Herald of Free Enterprise* have some significant similarities – the precipitating event was a moment of inattention, which was compounded by the inability of the mechanical systems involved to compensate for that failure. But the sinking of the *Herald of Free Enterprise* was the result of systematic organisational failures. It had failed to put in place measures to mitigate a risk that the owner of the ship was aware of. Furthermore, the fundamental design of that type of ship was susceptible to capsizing in the event that water found its way onto the car deck, an event that was entirely likely if the bow doors were left open. Once the stability of the ship was compromised a fatal outcome was almost inevitable due to the difficulty of escaping from the upturned hull, the heights that people would fall from within the ship and the amount of debris that was likely to fall on to them. By contrast the Selby incident demonstrated that, in a collision between a road vehicle and a train, the train would be unlikely to suffer catastrophic damage. It was not the fact that the express train struck the Land Rover that caused an incident of the scale that Selby became; it was the chain of unfortunate coincidences that was at fault – which caused the partially derailed express train to jump from the southbound to the northbound tracks and then strike the northbound freight train, at a point where both trains also collided with a bridge over the tracks.

3.3 Just one of those things?

Should we then view the Selby crash as "just one of those things"? Certainly, that was the view the subsequent enquiry took, concluding that there was no failure of rail infrastructure, the trains involved or the manner in which they were operated. The driver of the Land Rover was convicted of ten counts of causing death by dangerous driving and was sentenced to five years in prison, of which he served only half. It is not unreasonable to view his actions as irresponsible; the police investigation found that he had both stayed up all night before setting off on his journey in the early hours of the morning and driven at an excessive speed for the conditions, vehicle and load that he was carrying. But as was noted in the previous chapter, human fallibility is a given, and robust systems must be designed to cope with that fallibility. He had not set out to cause the collision. For him the circumstances of the incident had aligned to ensure the worst possible outcome. Had he fallen asleep and left the road a moment earlier or later then his vehicle would not have ended up in the position that it did, and the express train would not have struck it. Had he been a few minutes later then the express train would already have passed, and a few minutes earlier then his call to 999 might have been early enough for one or other of the trains to have been stopped before the collision occurred.

Was this incident "reasonably foreseeable"? The late John Prescott MP was minister for transport at the time. He convened an enquiry into the risks posed by vehicles leaving the road and causing an obstruction on the railway. That enquiry noted that "hundreds of thousands of vehicles leave the carriageway each year" (perhaps an overestimate but the point still stands), of which 50–60 end up on railway property, of which 20–30 end up on the track, of which 4–5 are hit by a train, of which 1–2 are derailed. Of those that are derailed approximately one in a hundred will then strike another train. In other words, in the view of the enquiry, an incident in which a train struck another train as the result of first striking a road vehicle was a once in 100–200 years event, and the risk of that collision being of the severity of the Selby incident a once in 300–400 years event.

Reasonably foreseeable is not the same as "frequent". It is entirely foreseeable that the Earth will be struck by a giant asteroid, which will potentially lead to the extermination of all life on the planet – such an event has happened at least once before, and we know that the solar system is swarming with objects of a size sufficient to cause devastation were they to strike the Earth again. But we don't expect Network Rail or National Highways to make contingency plans for such an event, despite the high level of certainty that it will happen at some point in the future. Network Rail and National Highways may, with some justification, claim that extra-terrestrial objects are not within the boundaries of their systems and consequently not for them to mitigate. But we might also take the view that global climate is not within the boundaries of the systems for which our national infrastructure operators are responsible and yet we still expect them to take action to mitigate the risk of large waves washing away railway lines or floods engulfing motorways.

Perhaps then it is not a question of whether a particular agency has control over a phenomenon that should determine whether it needs to include it in its systems models, but the likelihood that such a phenomenon might have a serious effect on the parts of the system that it does have control over. That inclusion must also be mediated by both the probability that a serious outcome might occur and the frequency with which it is likely to occur. In the case of severe weather events as a result of climate change, it is becoming harder to predict the frequency with which such events might occur since the system itself has become unstable. Thus "once in 500 years" floods or fires are becoming once in five years or once in a year events.

For emergencies driven by climate change, we can see the system evolving before us and are therefore justified in taking a much more cautious approach than historical frequency data might suggest. But what about once in 400 years events like Selby? Here the level of response that may be appropriate is likely to be mediated by the scale of the mitigation required. Few if any system-wide hazards that affect transport have a cheap “magic bullet” solution. Had the vehicle restraint system on the bridge over the railway been just a few metres longer then it would have directed the Land Rover back onto the carriageway and the incident would never have happened. But there was no way of knowing that the particular bridge would be the one where a vehicle would leave the road and end up on the railway. The solution proposed by the enquiry was to improve the methods used to assess the risk of a vehicle leaving the road and causing a catastrophic outcome. But when dealing with such infrequent incidents, the scale of the intervention is likely to be very large and the scale of the effect unmeasurable. However, this is not to suggest that systematic safeguards such as vehicle restraint systems are a waste of money and should be abandoned. Instead, the point is that we may never be able to justify the installation of any single metre of crash barrier, any more than we can justify the installation of any single fire door or any single first aid box, but viewed at a systemic level we know that those things have a positive effect on safety. Since every intervention has a cost associated with it, and carries some potential risk, the trick here is to ensure that the interventions we choose do not cause more harm than they prevent and are not so costly in time, money or other resources that they displace a more effective intervention elsewhere.

Key messages

- It is essential to understand where the boundaries of a system lie and whether those boundaries are permeable to outside influences or not.
- Systems may be susceptible to unpredictable outside influences that breach the boundaries of the system.
- Some interventions will only work if they are made in a systematic manner, and the individual effect of any single change may never be measurable on a reasonable time scale.

Related systems thinking tools

Boundary Judgements: Understanding where these boundaries overlap (e.g., level crossings) and ensuring appropriate interactions between the systems to minimise risk (Section 8.2.3).

Rich Pictures: Helps illustrate the complexity of the crash (i.e., Selby) and highlight areas where safety gaps exist due to unclear or overlapping system boundaries (Section 8.3.6).

Multiple Cause Diagrams: Aids in mapping how individual factors converge into catastrophic outcomes, helping identify points for intervention (Section 8.3.5).

System Dynamics: Helps understand long-term interactions between systems (e.g., road and rail systems) and the potential ripple effects of mitigation strategies (Section 8.2.12).

Control Models: Ensures system feedback mechanisms are robust and identifies vulnerabilities like the failure to detect a vehicle on the tracks (Section 8.3.3).

Failure Modes and Effects Analysis (FMEA): Identifies weak points where system failures (e.g., vehicle restraint inadequacies) could lead to accidents (Section 8.2.10).

Critical Systems Heuristics (CSH): Ensures that responsibilities for mitigation, such as between road and rail authorities, are well defined and inclusive of all perspectives (Section 8.2.4).

Socio-Technical Systems Theory (STS): Ensures that technical interventions (e.g., vehicle restraint systems) are supported by effective organisational policies and human oversight (Section 8.2.8).

Conceptual Modelling: Highlights gaps in system design and provides a blueprint for better integration of road and rail safety systems (Section 8.3.2).

Delphi Method: Helps generate insights on balancing safety investments between road and rail systems, such as prioritising vehicle restraint upgrades (Section 8.2.7).

Viable System Model (VSM): Assesses whether the current organisational and technical structures can respond to rare, high-impact events like the Selby crash (Section 8.2.13).

4 Complex adaptive systems – how to regulate a chaotic world

Cultures, both corporate and social, are a crucial part of the way systems function. When a new regulation is written, the effect it has will to a very significant extent be mediated by the cultures it interacts with. Culture is like a social algorithm, in the sense that a certain input tends to yield a certain output, which is mediated by that algorithm. For example, given the input of reaching December each year, many people will bring a tree into their house, put up brightly coloured lights and start buying confectionery in industrial quantities. There is no law that demands that people erect a Christmas tree and no penalty for failing to do so – but millions of people still do it. There is also no public information campaign that sets the date on which the tree must be erected, although the date of the festival itself is set (with some variation for different denominations). There is nothing formal to prevent anybody from erecting a tree in their living room in the middle of June, if they chose to do so, and a few do, but the cultural algorithm applies some pressure to reduce the frequency of such incidents. Culture then is clearly important – exercising a powerful but ephemeral effect on the way people behave. Culture is unwritten and different to the law, religion or constitution, although all may have an influence on the way a culture develops.

Many industries develop their own cultures, producing a set of beliefs and behaviours that moderate and mediate activities in the industry. Companies often write about their "culture", usually using terms like "integrity" or "responsibility", but those documents almost never capture the real nuance of how the culture of a company, or the industry in which it works, really operates. Culture might be better thought of as a set of habits. To a significant extent the things we do out of habit define our own personalities and that of the organisations we work for. If we have a habit of ensuring that all doors and windows are locked and all electrical appliances switched off before going to bed, our personality is likely to be very different to somebody who never bothers to check those things, and that habit is also likely to affect those we have social authority over – our children or siblings. Some industries are habitually cautious while others are less so. That caution breeds a whole series of habitual behaviours that many people working in the industry may not even be conscious of possessing, but which have an enormous effect on the culture of the industry. Industrial and organisational culture can affect things like attitudes to faults and failures – consider the relative reliability of the software on your computer or the walls of your house. We scarcely bat an eyelid when a spreadsheet freezes or webpage fails to load, even though we're confronted by those problems on a daily basis; but imagine your reaction if even a single brick fell out of the wall of your house the next time you shut your front door.

Clearly then, if we're trying to model the behaviour of a system that has people within it, we need to try to understand the cultural influences that are going to affect them. How are they likely to react to being told what to do? What do they believe about their social responsibilities? This applies equally to individuals, corporations and public bodies.

4.1 Micromobility, the scourge or saviour of the modern age

Depending on your viewpoint, micromobility is either the solution to all of our transport problems – it provides cheap, low-carbon, easily accessible mobility to the masses without clogging up the streets with gas-guzzling, pollution-spewing cars – or it is the scourge of the modern age – cluttering up the pavements, providing transport to thieves and drug dealers and wasting valuable resources on poor-quality disposable tat that will end up in a canal after six weeks. The reality of course is that it is probably both, at least to some extent.

Micromobility is a bit of a nebulous term and might mean anything from a pair of roller-skates, via e-scooters (of course) and cargo bikes, to a moped or microcar. Nebulous definitions are one of the problems we frequently encounter when trying to use systems thinking to improve safety. When you say car, do you mean Ferrari, or Smart Car, or eight-seat Land Rover? Definitions are also important when we're thinking about people, and, because the way we identify ourselves is important to us, they are potentially extremely contentious. For example, it's often said that "disabled people" hate e-scooters, because they clutter up the pavement and make it hard for them to get around. Except it turns out that some disabled people are actually very excited about the possibility of being able to use a relatively cheap, lightweight device to **help** them get around.

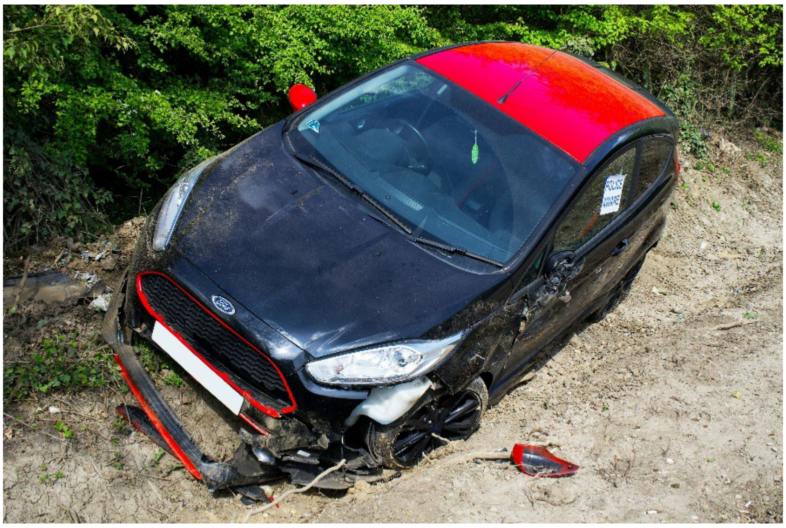
4.2 System boundaries

In the previous chapter we talked about system boundaries and the importance of understanding where systems might interact. In the Selby accident, two systems, which were supposed to be completely separate, came together in an unexpected way to cause an accident. When we look at micromobility, there really is a big challenge in understanding where the boundaries of that system are. For example, can we separate micromobility from building safety? On the face of it they seem to be very different domains, until you consider that micromobility devices need to be recharged, and that recharging is likely to happen inside a building – either somebody's home for private devices, or inside an industrial building for commercially operated ones. Now it turns out the fire service has a strong opinion on this new transport mode, and not for the reason some might expect.

So, can we separate micromobility from public transport? Also no – owners of private devices want to be able to carry them on trains and buses so they can use them for their "last-mile" journeys, and the operators of rental schemes are effectively acting as public transport operators – augmenting and even replacing more traditional forms. That means we need to think about the interfaces between micromobility and public transport – should we allow e-scooters on buses? Should we site rental pick-up points outside railway stations? Should we allow somebody with a travel card that allows them to travel by train, bus or ferry to also use that card to rent a cargo bike?

Can we separate micromobility from pedestrians or from other forms of road transport? Are micromobility users “pedestrians with wheels” or “slow motorists”? When we’re collecting casualty data, should we count somebody who has fallen off an e-scooter in the same column as somebody who tripped over on the pavement, or somebody who fell off a motorbike? Does it matter whether that e-scooter was a “legal” rented machine, or an “illegal” private one? All of this matters because from a regulatory perspective we view the world through a statistical lens.

The presence or absence of a suitable box to tick on a police form can have a very significant effect on the way we view the world, and hence the way we choose to regulate it. When a police officer ticks the box marked “car”, we can have a reasonable confidence that we’ll agree in principle on the vehicle that was involved. If that police officer writes “Ford Fiesta” on the form, we can also be confident that we’ll agree on what was meant. There may be some uncertainty of course – was it the three-door or the five, had the owner tinted the windscreen, did it have furry dice, or not? But fundamentally we know we’re talking about a vehicle with four wheels – not three or five, with the engine at the front, driving the front wheels, which crucially has been subject to type approval, and must therefore in essence be exactly the same as all of the other Ford Fiestas in the world. That allows us to make a judgement about whether it is safer to be in a collision involving a Ford Fiesta or an Audi A5, and which of those is most likely to have a collision in the first place, and consequently make recommendations to regulators about whether cars of the future should be more like the Ford or more like the Audi.



But when a police officer ticks a box marked “e-scooter”, what do they mean? Are they referring to a thing that has a seat, or not? Are they referring to a thing with a top speed of 15mph or 100mph? Do they mean a thing with two wheels, or three, or four… or one?

The reason that all of this is so complicated currently is that we have an important element missing from our system – we don’t have a well-developed standard taxonomy for micromobility machines. For cars and vans and trucks and buses and motorcycles we have a system that allows us to easily agree on the species, genus, family, order and so on that a particular vehicle belongs to. That taxonomy is governed by type-approval regulations, which ensures that "species" of vehicles are properly defined and identifiable and consequently we are able to draw valid conclusions about the factors that make them safe or otherwise. This system of standardisation of vehicle design is further augmented by standard annual tests of roadworthiness and a standard test for driver competence, although both could probably be improved. This is not to say that micromobility is made less safe by a lack of standardisation, although that might well be true, but instead the point is that we simply don't know in many cases what differentiates a good micromobility device from a bad one. The result is that regulators often turn to plausible but ineffective metrics for regulation, such as motor power or wheel size.

This lack of useful safety insight would not be such a problem if we were at the end of more than a century of development and testing, as is the case with many other modes. For those mature modes it is possible to some extent to rely on the organisational culture of the companies that design and make them to ensure that a reasonably safe product is produced. However, those companies are still to a significant extent hemmed in by regulations and standards to prevent those that might seek a commercial advantage via mischievous means from being able to release products that stray too far from currently accepted best practices. The micromobility industry has no such body of knowledge built up over decades, save for that it has been able to borrow from the adjacent bicycle and motorcycle industries. This lack of a well-developed industrial culture is further compounded by the fact that many of the manufacturers of these new types of vehicles have never built any type of vehicle before – entering the market either from other industries, mainly consumer electronics, or starting up as completely new companies. How then should these new companies, working in a new industry, decide what makes a safe e-scooter or unicycle?

4.3 The supply chain

One further complication with micromobility, which is perhaps unique in the transport world, is the way the supply chain operates. If you want to buy a new car, the chances are you will go to a dealership that is franchised to the manufacturer of the vehicle you want to buy. It will have a physical showroom, which will almost certainly be attached to a workshop capable of maintaining and repairing the vehicles it sells. The manufacturer will almost certainly not be British owned, but almost certainly will have a physical national headquarters in the UK and a physical international headquarters somewhere in the world. If your car breaks down and you want to march up to a physical place where it was made to complain about it, you almost certainly could. But if you want to buy an e-scooter or a hoverboard or an e-unicycle there is a fairly significant chance that it will arrive at your door in a cardboard box. There is a very good chance that the manufacturer will not have a physical national headquarters in the UK and a reasonable chance that the manufacturer only really exists in a theoretical sense – as a brand name rather than a physical organisation. If you want to return your malfunctioning e-scooter for repair, then you may be hard-pressed to confirm where and by whom it was actually made. This lack of traceability further compounds the lack of standardisation and regulation. If you can't tell who made your vehicle, or where it was made, then you also can't tell what level of quality it was made to and whether it is the same as another apparently identical machine or not. This also presents a significant challenge to any authority that might wish to provide guidance to, or take enforcement action against, the manufacturer of a particular product. This means that in many cases the only mechanism by which dangerous products can be prevented from being used is to confiscate them when they are found in use, or to seek to intercept them when they arrive in the country. Both methods require a significant level of effort and resources to achieve.

In the UK, micromobility devices that are neither pedal cycles nor type-approved L-category vehicles are illegal to ride in public places, but perfectly legal to buy and own. This has caused some confusion for the travelling public, who find themselves encouraged to use rental e-scooters in those areas where they are available, but prosecuted for using privately owned e-scooters, and other micromobility devices, which ostensibly appear to be identical. From an enforcement point of view this clear demarcation has at least made the job of identifying that a device is being used illegally quite straightforward, but it has done nothing to reduce the volume of such devices being ridden quite openly in the street. Since by definition riding a private micromobility device in a public place is against the law, the users of such devices might regard themselves as "outlaws", who as a consequence are not bound by any other road traffic law – if you're riding an illegal vehicle, it doesn't matter if you ride it on the pavement or through a red traffic light or the wrong way up a one-way street. That outlaw status also makes it very hard for authorities, who might wish to provide safety advice, to engage with users – is it okay for the police or the council to run an ad campaign explaining the safest way to ride an e-scooter when riding one in public is against the law? Would doing so be seen to be encouraging this illegal practice? The same is true of any physical intervention that might be made to support the use of micromobility devices. For example, it might be desirable to provide secure outdoor charging areas for e-scooters, to reduce the need for users to take them into their homes to charge and thus reduce the risk of dangerous domestic fires, but to do so would by definition be encouraging or at least facilitating the illegal use of those devices.

There may be something useful to learn here from the way many authorities deal with the use of illegal drugs. The use of injectable illegal drugs in particular is associated with a significant risk of contracting blood-borne diseases such as HIV and hepatitis, which are difficult and expensive to treat, create a disease reservoir, which may spread more widely within the population, and are life-limiting for those who contract them. These diseases may be regarded as a negative feedback loop for potential drug users – discouraging their use. But addiction is not that simple, and most people who become addicted to illegal drugs don't do so as the result of a carefully calculated cost–benefit analysis. In response to this problem, many authorities have set up needle banks where illegal drug users can freely access sterile needles and dispose of used ones. This could of course be regarded as facilitating illegal drug use, but the authorities concerned have decided that the economic and social burden of dealing with blood-borne diseases outweighs any potential (theoretical) increase in the number of people using illegal drugs. There are of course very significant differences between the social, economic and psychological factors that influence drug users and micromobility users, but the lesson may still be a valuable one. Seeking to reduce the number of offenders and seeking to prevent harm from coming to those offenders, and those around them, are not mutually exclusive. Indeed, if the purpose of the criminal law is to prevent harm to the public then providing guidance and even facilities for "offenders" is completely aligned with that goal.

Ultimately of course the solution may be to legalise the use of some or all micromobility devices in public places. This will require standards to be set for the acceptable performance of such machines, just as they are for other modes. It is also likely to require some restrictions being placed on the manner in which these machines can be ridden, and by whom.

Key messages

- Culture can exercise significant influence over social and organisational behaviours.
- It takes time for culture to develop in new industries and for that culture to begin to exercise its moderating effect on the way those industries function.
- The goals of reducing harm and upholding the law may not always be fully aligned. If given a choice, always try to reduce the harm first.

Related systems thinking tools

Socio-Technical Systems Theory (STS): This theory is ideal for analysing and designing systems that involve both technical and social components like micromobility systems. It can help assess how micromobility interacts with public transport pedestrians and broader societal systems (Section 8.2.8).

System Dynamics: This tool helps model feedback loops and time delays in systems like micromobility regulation. It can be used to simulate interactions between micromobility devices infrastructure and other road users to inform regulatory approaches (Section 8.2.12).

Delphi Method: Useful for gathering expert opinions on complex regulatory issues such as developing standards for micromobility devices or assessing their integration into public transport systems (Section 8.2.7).

Stakeholder Analysis: This approach can help identify and engage key stakeholders in micromobility such as manufacturers users public transport operators and regulatory bodies (Section 8.2.6).

Strategic Options Development and Analysis (SODA): This is relevant for exploring regulatory pathways such as whether to legalise private micromobility devices or create incentives for shared schemes (Section 8.2.9).

Viable System Model (VSM): This conceptual model can diagnose and design systems that maintain viability in dynamic environments ensuring that micromobility regulations are resilient and adaptive to changes (Section 8.2.13).

Systems Maps: To represent the boundaries and interactions between road and rail systems highlighting points of overlap such as level crossings (Section 8.3.9).

5 Looking to the future – systems thinking in a (semi) automated world

5.1 Flying is dangerous!

Flying is dangerous. Everybody knows that. Hurtling through the sky at 30,000 feet at 500mph with nothing between you and oblivion but a millimetre of aluminium – barely the thickness of a drinks can. But 2023 saw no losses of any passenger jet aircraft anywhere in the world and only a single loss of a scheduled commercial passenger aircraft. Of all the transport modes, aviation is the most heavily regulated and arguably the safest as a result.

Aviation and powered road transport are effectively siblings, having both been invented and developed their early popularity around the turn of the twentieth century. But while aviation quickly developed a robust scheme of technical and user regulations, augmented by a sophisticated accident investigation apparatus, road transport has always taken a much less formal approach to regulation and accident investigation. These differences in approach are perhaps justified given the relative complexity of the vehicles involved, the level of skill required to operate them safely and the potential number of lives lost in a single mishap. But when considered in the context of around 1.2 million road deaths globally per year, the casual approach taken to road vehicle safety seems dangerously cavalier. As we consider the possibility of new modes of transport emerging in the coming years, how should we apply the lessons learned from aviation, road and other modes to the development of a safe transport system?

5.2 How to fly a plane

Lesson #1 in how to fly a plane – you **must** keep the wing moving forward through the air. Over the years, thousands of pilots, and their unfortunate passengers, have died because they forgot that crucial first lesson. The speed of an aircraft is measured relative to the air around it, not the ground. On a windy day a fixed-wing aircraft can hover motionless above the ground with its airspeed indicator showing 50mph. New pilots are taught about the importance of combining the control of the engine's power with the attitude of the aircraft to make the aircraft go up or down while ensuring that the crucial airflow across the wing is maintained. When the airflow over the wing slows down to the point where it starts to break away from its upper surface, a condition known as a stall, every new pilot knows that the treatment is to push the nose down towards the horizon and increase engine power, thus increasing the speed of the air over the wing sufficiently to start creating lift again.

While for many light aircraft the stall is quite a benign, almost unnoticeable event, which is easily recovered from, for heavier aircraft stalling can be a dramatic affair requiring thousands of feet of altitude to recover. In 1988, Airbus introduced the A320 airliner, which nowadays is a common sight on short- and medium-haul airline routes all around the world. One of the unique selling points of the A320, and all subsequent Airbus airliners, was its fly-by-wire control system, which replaced the mechanical or hydraulic connections between the controls in the cockpit and the aerodynamic control surfaces on the wings and tail, with an electronically actuated system controlled using an armrest-mounted joystick, much more like a fighter aircraft than the chunky control wheels seen in other airliners. This system also removes the mechanical connection that traditionally links the flight controls of the two pilots, instead using a selector switch to allow the pilot flying the aircraft to select their joystick as the one that controls the aircraft. The flight control system of the Airbus does far more than simply replace a mechanical connection with a more modern electronic alternative. Between the controls in the cockpit and the control surfaces on the wings and tail, a complex system of computers monitors the performance of the aircraft to ensure that it remains inside a stable flight envelope and is able to overrule commands from the cockpit in situations where the pilot puts the aircraft into a dangerous situation like a stall.

The speed of an aircraft through the air is determined by measuring the difference in pressure between a tube pointed into the airflow and a port on the side of the aircraft that measures the static pressure of the air outside. The forward-facing tube is known as a pitot tube and in its simplest form is just an empty tube connected to the airspeed indicator, although most also include a heating element to prevent the pitot tube from becoming blocked with ice.

In flight the job of an airline pilot is largely to supervise the automation system that is actually flying the aircraft. The automated control systems of airliners are able to manage almost all flying tasks without assistance from the crew. As commercial aviation has matured over the twentieth century, the job of pilots has changed from physically flying the aircraft – controlling its movement with hand and foot controls – to programming the automated flight control system and monitoring it to ensure it doesn't deviate from the intended route. Human intervention is only required when something goes wrong, or the aircraft encounters conditions that are beyond the capability of its flight control system, such as strong crosswinds while landing.

5.3 What makes aviation so complex?

Flying is a very simple process – push a wing through the air at enough speed to generate lift and then steer. But commercial aircraft are complicated machines, which operate as an integrated part of a very complex system. At a mechanical level the complexity has arisen in part because of the size of airliners – big things are almost always more complex than small things. Airliners all have at least two engines, and many have three or four, which means they have two, three or four sets of engine systems – fuel pumps, gauges and their associated sensors, lubrication systems and so on. They have hundreds of seats, each with its own reading light, call button, air vent and emergency oxygen supply. They are built to be extremely light for their size, which means their structures are much more intricate than a sea or land vehicle. The process of controlling aircraft is more complex than for a land or sea vehicle because of their ability to move in three dimensions. That extra dimension also means they can rotate about two extra axes, so while a land or sea vehicle only needs to be steered from side to side and controlled in the forward and backward directions, aircraft also need to be controlled in roll and pitch. And that control in three dimensions and around three axes needs to be achieved entirely by manipulating the flow of air over control surfaces on the wings and tail.

That mechanical (and electronic) complexity means that the people who fly and maintain aircraft need a greater amount of knowledge than their counterparts on land or in the sea. The intricacy of aircraft systems also makes them more sensitive to the ways in which they are used and maintained and less resilient to wear and fatigue – necessitating an even greater level of maintenance and inspection. Just like seafarers, pilots must also have the skills necessary to navigate over long distances, out of sight of land, and must understand the effects of weather on the control and navigation of their craft.

Mechanical complexity, and the complexity of the task, leads to organisational complexity. Aircraft must be carefully designed, manufactured and tested according to a strict set of standards and regulations. Each component, no matter how mundane, must be carefully analysed and certified. The people installing those components must be properly trained and licensed. Records must be kept of every modification, repair or replacement made. Since it's not possible to paint white lines in the sky, aircraft must operate under a strict system of air traffic control, which ensures that aircraft are kept apart. That air traffic control system must be properly equipped with radar and communication systems, which must be installed and maintained by certified engineers and operated by properly trained and licensed operators. Aircraft must be provided with detailed weather reports and forecasts covering routes thousands of miles long, drawing weather data from a global network of weather stations and satellites, interpreted by trained meteorologists using complex computer models of climate and weather. And all of those things must be done at a global scale, across thousands of aircraft carrying millions of passengers on routes from Anchorage to Buenos Aires and Addis Ababa to Ulaanbaatar.

In every part of the system there is the potential for a tiny error to lead to a catastrophic failure – a switch wrongly set in the cockpit, a number misread by a fuel truck operator, a sudden thunderstorm where none was expected, a message misheard on the radio. And yet that mindbogglingly complex, hazard-infested system operates almost impeccably – why is that?

5.4 Organisational culture

The aviation industry is exceptionally conservative. The A320, in service since 1988, is not an outlier; if anything, it's a relative youngster – the Boeing 737 has been in service since 1968. Changes happen very slowly. The design process for a new airliner is extremely long – the project that ultimately led to the Airbus A380 started in 1988 and didn't have its first commercial flight until 2007. That conservatism sacrifices cutting-edge modernity for proven reliability. The scale of an airliner design project means that only a handful of companies in the world have the resources necessary to undertake one. That means that knowledge is concentrated, and company culture has had a long time to mature. It's interesting to reflect on the recent problems at Boeing, which seem primarily to have been brought about by a change in management and consequent disruption to the company's culture.

One important facet of aviation culture is the importance of reporting, investigating and publicising every incident, no matter how minor. Every day somebody bumps their car into another car in a supermarket car park and makes a small but irritating dent. That incident might be reported to an insurance company. If you drive off without saying anything, it might be reported to the police. But there's no chance that a report on the investigation of that minor incident will make it into the pages of *Auto Express* or *Top Gear* magazine. But if you had the same minor bump in an aircraft then a report would be prepared by the Air Accident Investigation Branch (AAIB), published on its website for all to read and very likely summarised in the monthly review of incidents that appear in every issue of *Pilot* or *Flyer* magazine. Indeed, a pilot doesn't even need to have an actual collision to feel the need to make a report – lining up on the wrong runway or selecting the wrong fuel tank is often enough for a pilot to confess to the AAIB. In addition to the formal incident reporting system administered by the AAIB, a charity called CHIRP (Confidential Human Factors Incident Reporting Programme) runs its own system for collecting confidential, voluntary incident reports from pilots (and mariners), with the sole purpose of sharing the learning that can be derived from the mistakes made by others. In aviation, at every level from hang-gliding to space flight, reporting incidents in order that others might learn from them is a central pillar of the "safe system". By contrast, the prosecution of pilots for errors made is rare. The attitude of the industry and its regulators is that it is much better to learn the holistic lessons from an incident in order that it can be avoided in the future than to seek to punish those involved.

5.5 Flight 447

Air France flight 447 left Rio de Janeiro at 19:39 on the 31st of May 2009, bound for Paris. The service was operated using an Airbus A330 – the larger four-engine cousin of the A320. The route took the aircraft north along the coast of Brazil before turning slightly west onto a heading that would take it across the Atlantic, before skimming the coast of Africa and crossing Spain, landing in Paris approximately ten and a half hours later. For this relatively long route the aircraft carried three flight crew – a captain and two first officers, who would take turns to rest and supervise the flight control systems.

Approximately three and a half hours into the flight the aircraft encountered thunderstorms over the Atlantic. This was not unusual on this route, which passed through the often stormy mid-oceanic tropical zone. The strong updraughts buffeted the aircraft and created hail, which started to stick to the airframe. A few minutes after encountering icing conditions inside the storm, the autopilot disengaged. Ice had clogged the pitot tubes, robbing the flight computers of their airspeed information, which is critical for the calculations used to keep the aircraft within a stable flight envelope.

The pilot in the right seat immediately took over manual control of the aircraft, pushing the joystick from side to side as he struggled to compensate for the rolling action created by the turbulent rising air. While battling to level the wings he began to pull back on the joystick, pushing the aircraft into an abnormally steep climb. As it climbed, the speed of the aircraft began to decay. The throttles were advanced to full power to compensate, but still the pilot in the right seat pulled hard back on the joystick. An alarm sounded, indicating that the wings had stalled, and the aircraft began to fall down towards the ocean. Unable to process the partial information that the instruments were giving him, the pilot continued to pull hard on the joystick and even used the trim system, which is intended to make adjustments to the aircraft's attitude so that it can be flown with hands off the joystick, to pull the nose up even further. The pilot in the right seat had lost his mental picture of what the aircraft was actually doing, misinterpreting instruments and alarms as a sign that the aircraft needed to climb. But pointing steeply nose up with throttles at full power, the aircraft was actually falling rapidly as the wings could no longer generate any lift. The sophisticated fly-by-wire system, designed specifically to avoid this type of pilot-induced departure from stable flight, was powerless to intervene – rendered useless by a few grams of ice in a metal tube.

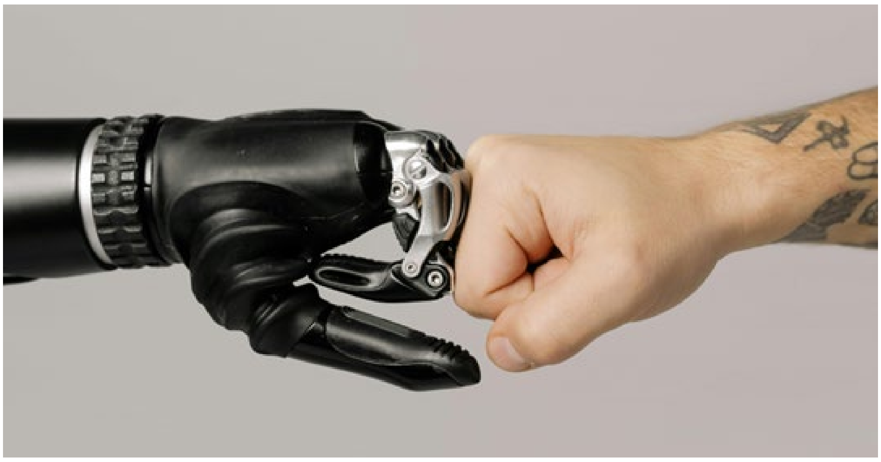
As the aircraft fell faster and faster towards the water, the pilot in the left seat recognised what was happening. He pressed the button to switch control to his joystick and pushed the nose down to reduce the angle of the wings and correct the stall. But the pilot in the right seat was still hauling back on his joystick. With no mechanical connection between the controls, both pilots could enter opposing commands via their respective joysticks. Confused by those opposing commands the flight computer announced "Dual input". To confuse things even further, the stall warning alarm, which should have alerted the pilot to his mistake, was designed to switch off when the aircraft exceeded a certain angle relative to the airflow. The aircraft had gone beyond the limit it ever expected to encounter. Meanwhile the pilots understood that the flight computers should prevent the aircraft from ever being able to stall, but that feature had become inoperable when the computers started to receive unreliable airspeed information.

If he'd been flying a First World War biplane with a control system made out of string and sticks the pilot in the right seat would almost certainly have recognised his mistake, relaxed his grip on the joystick and allowed the wing to bite into the air and resume stable flight. But he had become so confused by the cacophony of alarms and information, some accurate, others not, that bombarded him, while his own mental model of what the aircraft ought to do was so at odds with what was actually happening, that he simply couldn't see a solution in time to prevent the aircraft from plunging into the ocean. A moment before impact, realisation of what was happening dawned on the captain. "No, no, no, don't climb! No, no, no!" The pilot in the left seat once again took control and pushed the nose down. But by now the aircraft was only a few hundred feet above the water. As the nose came down and the wing briefly started to regain lift the flight computer announced "Pull up!". The pilot in the right seat did as he was told, and doomed the aircraft and its 228 occupants to the ocean.

5.6 I'm sorry, Dave, I'm afraid I can't do that

The spectre of malign artificial intelligence has become one of the mainstays of dystopian science fiction. In Stanley Kubrick's epic 1968 film *2001: A Space Odyssey* HAL, the computer controlling a spacecraft on a mission to Jupiter, turns against the human crew and sets out to kill them – using deceit and setting deliberate traps to lure the crew to their deaths. Experts in the field of artificial intelligence are becoming increasingly alarmed that such a scenario might play out in real life. But our relationship with automated systems already poses a real threat. On flight 447 the onboard computer system had no murderous intent, but the relationship the crew had formed with it left them unable to defend themselves when what should have been a very minor failure led to a catastrophic breakdown in situational awareness. That breakdown was made more likely by the crew's previous experience that the computerised system would prevent them from doing anything that could endanger the safety of the aircraft. When that safety net was lost, it not only took away the protection that the automated system would normally provide, but it also took away the protection that the crew themselves could provide.

So, what should we do? Modern flight control systems are perfectly capable of operating an aircraft in almost every scenario. But who would be happy to board an aircraft knowing that there were no humans in the cockpit? Human pilots have been flying across the Atlantic for over a hundred years without complex computerised flight control systems, but many of them have ended up in the ocean as a result of some minor error or miscalculation. In time of course the capabilities of computerised systems will get better. According to technology folklore, the computers that helped the Apollo missions to land on the moon had less processing power than a digital calculator, and the computers in an Airbus almost certainly are less capable than a smartphone today. But that rapid development in computing power has largely been the result of a very low-stakes game, where failure is an integral part of the product experience. Has your laptop crashed again? Go and make another coffee while it restarts.



As we entrust automated systems with ever more responsibility for our safety, we need to ensure that the cavalier attitude that has made the tech industry so financially successful is tempered by some of the conservatism that is such an integral part of the culture of industries like aviation. A completely automated system may be safer than one that is open to human interference, provided it remains within its normal operating parameters, but in order to be useful to people those automated systems are going to have to interact with us, and all of the variety that we bring to situations – our habits and beliefs, our knowledge and understandings, our attitudes to risk and propensity for mischief, and our skills and disabilities. If we are to defer responsibility for our safety to an automated system then it is imperative that we take responsibility for the proper design, construction, maintenance and operation of that system. We cannot cross our fingers and hope for the best that the machines will always look after us. We must always be sure that we are in control of the system.

Key messages

- The more complex a system becomes, the more vulnerable it will be to failure. Robust systems can help to ensure that failures don't propagate and that their consequences are mitigated.
- As we seek to delegate responsibility for safety to automated systems, we must ensure that we create robust organisational systems to regulate and maintain them.
- Automated systems don't need to have malign intent to have catastrophic effects. We must ensure that humans are properly prepared to work alongside automated systems and that humans always remain in control of those systems.

Related systems thinking tools

System Dynamics: To model interactions between human operators, automation, infrastructure and the broader transport system (Section 8.2.12).

Socio-Technical Systems Theory (STS): To understand the interplay between technological systems, human behaviour and organisational structures (Section 8.2.8).

Failure Modes and Effects Analysis (FMEA): To systematically identify potential failures in safety-critical systems (Section 8.2.10).

Control Models: To map feedback loops within operational and organisational safety systems (Section 8.3.3).

Critical Systems Heuristics (CSH): To evaluate and critique transport systems' assumptions and decision-making processes (Section 8.2.4).

Boundary Judgements: To define the scope and responsibilities within transport safety systems (Section 8.2.3).

Rich Pictures: To visually summarise complex transport systems and their interdependencies (Section 8.3.6).

Multiple Cause Diagrams: To explore the root causes of transport safety incidents (Section 8.3.5).

Delphi Method: To build expert consensus on emerging safety challenges (Section 8.2.7).

Viable System Model (VSM): To design resilient safety systems (Section 8.2.13).

Conceptual Modelling: To compare current safety systems with ideal models (Section 8.3.2).

Strategic Options Development and Analysis (SODA): To explore pathways for improving transport safety; helps identify strategies for integrating emerging technologies or regulatory changes (Section 8.2.9).

Backcasting: To envision a future of safe, integrated transport systems (Section 8.2.2).

SWOT Analysis: To evaluate transport safety systems' strengths, weaknesses, opportunities and threats (Section 8.2.11).

Part Two

Tools for systems thinking

6 Introduction

According to the IHME (Institute for Health Metrics and Evaluation, 2024) over the past three decades transport-related deaths have accounted for around 2.25–2.5% of all deaths globally. In many developed countries these rates have fallen below 1% of all deaths. Within the UK, for example, in 2022, there were a total of 1,755 transport-related deaths recorded, of which 1,711 were associated with road transport (Department for Transport), 11 with rail transport (ORR), 22 maritime (MAIB) and 11 aviation (AAIB). However, in many other countries the rates of transport-related deaths have been steadily rising.

Transport-related deaths do not account for the same proportion of total fatalities across all parts of society. The WHO (World Health Organization, 2023) reports that road traffic injuries are now the leading cause of death for people aged 5–29 years, as well as accounting for more than half of all road fatalities occurring among vulnerable user groups.

For many, transport can be a significant risk to life while also providing a critical service. This presents a challenge to those involved in the management and operation of these systems. The consensus among practitioners in the field is that transport is a complex socio-technical system (Salmon *et al.*, 2012). This feature is important given that conventional thinking, when applied to complex systems, can often be counterproductive in resolving issues. Experienced systems thinking practitioners and academics (Reynolds and Holwell, 2010) suggest this is because often with conventional thinking:

- interconnections can be ignored,
- a single cause may be assumed,
- blame can be assigned to an individual, and
- there may be a focus on only what can be measured.

Practitioners of systems thinking espouse that their approaches provide ways of selectively handling complex situations in order to reveal the underlying features of a situation from a set of explicit perspectives. These insights can then be used in order to make change that is hopefully desirable and culturally feasible.

6.1 Systems thinking for civil servants

The UK Government recently published introductory guidance for all civil servants on systems thinking and what it describes as accessible tools (Government Office for Science, 2023). In alignment with existing policy development processes, 11 tools have been identified and recommended for use. These include Rich Pictures, Pig Models, Context Diagrams, Behaviour Over Time Graphs, Enablers and Inhibitors, Systems Mapping, Map Analysis and Narrative, Identify Leverage, Stock and Flow Diagrams, Theory of Change Maps, and Monitoring and Evaluation strategies.

These tools were chosen based on their relevance and accessibility for civil servants, requiring no prior knowledge of systems thinking. By encouraging the use of these tools and providing a suite of support documents, the intention is to better equip civil servants with the approaches needed to deliver desired outcomes in complex situations.

Transport systems are inherently complex socio-technical systems, where safety issues often arise from interconnected factors that cannot be resolved using reductionist approaches. Conventional thinking, when applied to such systems, can lead to counterproductive outcomes by ignoring interconnections, assuming single causes, assigning blame to individuals or focusing only on measurable aspects (Reynolds and Holwell, 2010). Systems thinking provides a holistic perspective, enabling practitioners to address interconnections, feedback loops and emergent properties within these systems, enabling culturally feasible and desirable change.

The Government manual focuses on practical steps to help civil servants, transport operators and policymakers adopt and apply systems tools tailored to transport safety. Building on recent UK Government initiatives, it develops the themes introduced in Part 1 by identifying tools and methodologies specifically suited to addressing the complexities of transport systems.

The Government Office for Science's introductory guidance on systems thinking provides a valuable foundation for this work. Its relevance lies in the parallels between policymaking and the development, operation and use of transport systems, both of which demand holistic approaches to managing complexity and enhancing safety outcomes.

6.2 Objective for this work

This report is intended to augment the guidance provided by the Government Office for Science by providing an extended palette of systems thinking tools whose use has been demonstrated in the transport sector and transport safety. The purpose of this study is to identify and assess the suitability of systems tools with regard to their application in the safe development, operation and use of transport systems. While safety remains central, the report also examines broader aspects of transport performance, recognising that many tools contribute to efficiency as well as safety. In doing so, the intention is for these insights to help inform the broader development of integrated transport networks as well as reducing safety risk to all parties.

6.2.1 Definitions

Before investigating possible systems tools, it is important in the context of this report to define what is meant by the term tool. Like many disciplines, the fields of transport and systems have unique and sometimes contradictory vocabularies.

For example, within the transport field the meaning of tool can vary depending on the context. A tool could refer to a physical implement used to manipulate an object, a piece of software or a part of the wider infrastructure like a road or sign. Within the systems discipline, tool can refer to an approach, method, technique, practice or procedure that assists the practitioner in investigating, defining and changing the system (or an aspect of it).

It is this latter meaning that we will use within this report, that of a tool not simply being a physical implement but rather something that is used in the process of change-making. This choice reflects the need to achieve the study's objective (see Section 6.1) focusing on the application of tools at the macro levels of systems design, management and operation.

7 Method

The following method was adopted to ensure that the main objective of the study was fulfilled. The first stage was an evidence review, which identified a range of high-quality literature available on the use of systems tools in transport (see Section 7.1). The second stage involved a critical appraisal of the various system tools identified, establishing their suitability for supporting the safe development, operation and use of various transport modes (see Section 8).

The results of this review, assessment and analysis can be seen in Section 8. The work was used to inform recommendations on possible adoption of such approaches within the transport management industry.

7.1 Desktop review

The evidence review focused on academic studies that analysed and evaluated the application of systems tools across various parts of the transportation sector. The work included rapid evidence searches, abstracts screening, and full-text reviews and assessment. The aim was to gather a comprehensive understanding of how systems tools are applied within the transport sector to enhance safety and operational effectiveness.

7.1.1 Review strategy

To identify relevant studies, a series of key search terms (see Section 7.1.2) were developed based on the research objective. These terms were carefully selected to ensure coverage of the various elements of systems thinking and transport safety. They were selected based on:

- a common historic emergence in dealing with complex situations, and
- their prominence and use among practitioners with experience of their application as systems thinking approaches, and their demonstrated effectiveness in achieving desired outcomes across different transport modes.

Searches were then undertaken using Google Scholar to streamline the process and ensure broad access to high-quality academic sources. This approach ensured the efficient identification of relevant studies, prioritising top search results that were influential within the research area. As a database, Google Scholar contains a range of literature covering transport safety as well as a wider range of topics such as systems thinking.

7.1.2 Search terms

Table 1 shows the key search terms used for the evidence review strategy, structured to ensure that literature was captured at each level. The search used three levels. The first level used broad search terms that defined the general topic of interest, such as “Soft Systems Methodology”. The second introduced system tools, and the third used more specific terms related to transport modes, such as “Rail”, “Road”, “Aviation” and “Maritime”.

By combining these terms with Boolean operators like "AND" and "OR" at each level, the search became progressively more focused and yielded highly relevant and specific literature on the subject. Multiple combinations of search terms were used to ensure a thorough exploration of the available articles within Google Scholar. For example, the search query "Soft Systems Methodology AND Rail OR Road OR Aviation OR Maritime" was used to identify studies applying Soft Systems Methodologies across different transport modes.

Table 1: Key search terms used for the evidence review strategy

Level 1
Soft Systems Methodology
Critical Systems Heuristics
Viable System Model
System Dynamics
Strategic Options Development and Analysis
Socio-Technical Systems Theory
Activity Sequence Diagrams
Backcasting
Boundary Judgements
Causal Loop Diagrams
Cognitive Mapping
Conceptual Modelling
Control Model Diagrams
Delphi Method
Influence Diagrams
Multiple Cause Diagrams
Rich Pictures
Spray Diagramming
SWOT Analysis
Root Definitions
Systems Maps
Failure Modes and Effects Analysis
Stakeholder Analysis
Critical Systems Thinking

AND/OR Level 2
Tools
Approaches
Methods
Methodologies
Techniques
Practices
Procedures
Instruments

AND/OR Level 3
Rail
Road
Aviation
Maritime

7.1.3 Inclusion criteria

The following criteria were used for the search to ensure the relevance and quality of the studies reviewed:

- the studies were written in English,
- publication was via an open access source, and
- application was associated with the core transport modes of road, rail, aviation and maritime.

7.2 Tool assessment

The tool assessment focused on investigating the application of the various systems tools across respective transport modes. The work included the creation of brief technical summaries for each tool, a review and mapping of a tool's application across the transport modes, a categorisation of the tools by type, a SWOT analysis of these categories and a gap analysis to identify any opportunities for further application.

8 Results

8.1 Available evidence

This investigation conducted a comprehensive review of 91 separate studies examining the application of various systems tools across different transport modes. The breakdown of the systems approaches, and their respective transport modes, is as follows:

- **Road sector:** A total of 16 studies applied various systems approaches, with a strong focus on System Dynamics and Soft Systems Methodology, to address transport safety, risk management and operational efficiency in road transport. Common topics explored included traffic congestion, road safety frameworks and integration of smart technologies to optimise road network performance. System Dynamics was particularly useful for simulating traffic flow and collision prevention measures, while Soft Systems Methodology was employed to tackle complex problems like urban mobility planning and stakeholder management.

- **Rail sector:** Out of nine studies, the use of System Dynamics, Soft Systems Methodology and Delphi Method was prominent, particularly in enhancing system performance, infrastructure management and safety improvements in rail transport. System Dynamics helped model rail congestion, collision prevention and the impact of infrastructure upgrades on performance and safety. For example, one study assessed the comprehensive impacts of urban rail transit systems on traffic, economy, society and the environment, finding that urban rail transit reduces congestion and improves air quality while presenting challenges in economic and social development. Another study investigated the determinants of autonomous train operation in rail freight, identifying investment costs, safety, energy savings and reliability as critical factors for implementation. Moreover, Soft Systems Methodology was used to frame challenges related to integrating autonomous trains into existing infrastructure, highlighting stakeholder concerns and operational flexibility solutions. The studies collectively emphasise the importance of addressing safety, efficiency and community impacts within the rail sector.

- **Maritime sector:** In the 16 studies focusing on maritime transport, System Dynamics was the primary tool, frequently employed for simulating shipping operations and risk analysis. A few studies also utilised Socio-Technical Systems Theory to tackle complex logistical challenges. For instance, one study reviewed the application of System Dynamics in maritime transportation, highlighting its utility in understanding multimodal interactions and disruption management. Another study examined the future of Vessel Traffic Services in the context of maritime autonomy, advocating for a systemic evaluation of both internal and external consequences of design changes. Furthermore, studies assessing the impacts of climate change on maritime industries identified significant risks, including sea-level rise and altered shipping routes. Additionally, Stakeholder Analysis was employed in various studies to enhance collaboration and sustainability in maritime operations, contributing to a holistic understanding of the maritime system's dynamics.

- **Aviation sector:** 14 studies focused on aviation. Key systems approaches included System Dynamics, Delphi Method, SWOT Analysis, and Failure Modes and Effects Analysis (FMEA). These approaches were applied to improve flight safety, air traffic management and operational efficiency. Many studies examined the optimisation of flight routes, the impact of air traffic congestion on safety and the role of predictive tools in mitigating aviation risks. Some studies also looked at the integration of emerging technologies, such as autonomous aircraft systems and their potential to reshape future aviation safety protocols.

- **General transport studies:** In total, 36 studies examined various combinations of transport modes, employing different systems approaches to address the complexities of transport systems. Several studies focused on overarching themes applicable across all transport modes, utilising approaches like System Dynamics and Causal Loop Diagrams to explore sustainability and efficiency in transport systems. A number of studies specifically addressed the integration of rail and road transport, highlighting the interplay between these modes in relation to intermodal logistics and infrastructure development. Some studies explored the governance and operational dynamics of intermodal transport systems, utilising approaches like Stakeholder Analysis to assess roles and impacts. Other studies examined specific combinations of transport modes, focusing on unique challenges and opportunities that arise from integrating different systems.

Across all modes, the studies demonstrated the increasing relevance of systems thinking tools in addressing transport safety challenges, with each mode benefiting from different systems approaches based on its unique operational characteristics. A bibliography has been provided as an appendix to this document, which includes links to each source reviewed.

8.1.1 Categorisation of tools

Various systems thinking tools were identified and they have been defined, with examples of their evidenced use within the various transport modes captured. This information provides a grounding for further assessment and categorisation, with the intention of identifying suitable tools to support the safe development, operation and use of transport systems, as outlined in Section 6.1. Among the various tools listed, two broad categories can be observed. First is the category of approaches or methodologies, and then that of tools used to communicate systems thinking ideas. The tools are therefore categorised into two broad groups based on their purpose and complexity.

1. **Approaches or methodologies:** These are structured, high-expertise processes such as Soft Systems Methodology (SSM) and Boundary Judgements. They are designed to comprehensively diagnose and address systemic challenges, often involving multiple stages of analysis and stakeholder engagement.

2 **Communication tools:** These are simpler visual aids, such as Rich Pictures and Multiple Cause Diagrams, which support systems thinking activities. Communication tools can serve two primary purposes: (1) as artefacts, presenting the results of systems analysis (e.g., summarising causal factors contributing to a collision), and (2) as facilitation aids, enabling stakeholders to collaboratively explore and align their perspectives (e.g., collaboratively creating a Rich Picture during a workshop).

Table 2 provides a breakdown of tools by category.

Table 2: Categorisation of systems tools (alphabetically)

Approaches or methodologies	Communication tools
Backcasting (8.2.2)	Activity Sequence Diagrams (8.3.1)
Boundary Judgements (8.2.3)	Causal Loop Diagrams (8.2.12)
Critical System Heuristics (CSH) (8.2.4)	Cognitive/Causal Mapping (8.2.9)
Critical Systems Thinking (CST) (8.2.5)	Conceptual Modelling (8.3.2)
Delphi Method (8.2.7)	Control Model Diagrams (8.3.3)
Failure Modes and Effects Analysis (FMEA) (8.2.10)	Influence Diagrams (8.3.4)
Socio-Technical Systems Theory (STS) (8.2.8)	Multiple Cause Diagrams (8.3.5)
Soft System Methodology (SSM) (8.2.1)	Rich Pictures (8.3.6)
Stakeholder Analysis (8.2.6)	Root Definitions (8.3.7)
Strategic Options Development and Analysis (SODA)(8.2.9)	Spray Diagramming (8.3.8)
SWOT Analysis (8.2.11)	Systems Maps (8.3.9)
System Dynamics (8.2.12)	-
Viable System Model (8.2.13)	-

Approaches and methodologies cover the more complex tools, which are more typically processes requiring understanding of various systems thinking concepts, such as framing, perspectives, interrelationships and regulatory loops. Communication tools on the other hand are more typically diagramming conventions or tools that form part of a wider approach or methodology but can be undertaken with minimal systems knowledge (such as the development of Root Definitions).

8.2 Systems thinking approaches and methodologies

The following sections outline the various prominent systems thinking approaches and methodologies whose application has been mapped across transport modes. The sections provide a brief summary of each of these tools, where appropriate with detailed example diagrams, and highlight evidenced examples of the application of these tools within the various transport modes, where they exist.

8.2.1 Soft Systems Methodology (SSM)

Soft Systems Methodology (SSM) is used to understand an existing system. The approach is an organised way of tackling perceived problematical situations, and it has a broad application area given its ability to act as a learning system that generates improvement actions. Key components (Morey *et al.*, 2023; Checkland and Poulter, 2010) include:

- Rich Pictures used to visually express the problem situation.
- Root Definitions and CATWOE Analysis, which helps to define the system's purpose and assess its transformation potential from different perspectives (Customers, Actors, Transformation, Worldview, Owners and Environment).
- Conceptual Models developed to compare ideal situations with real-world conditions, allowing stakeholders to identify feasible changes.

There is published evidence of SSM being applied within various transport modes, along with broader multimodal systems. It has, for example, been used (Große, 2022) to understand how policy and governance at multiple levels (local, regional and national) influence the development and use of transport systems. The study also investigated the relationships between transport infrastructure and regional growth, particularly in remote areas. The focus was on multiple transport modes, including road, rail, air and sea transport, in the context of Swedish infrastructure development. The method was employed to structure the investigation of the transportation system, using Conceptual Modelling and Rich Pictures to capture the complexity of multi-level governance and stakeholder needs. The methodology enabled the identification of critical infrastructure needs and facilitated discussions about possible improvements to Sweden's transport policies and systems. This holistic approach helped build a shared understanding of the system among various stakeholders.

Another example (Suranata *et al.*, 2021) aimed to facilitate economic growth through improved connectivity between regions, specifically the construction of the Gempol-Banyuwangi toll road in Indonesia. However, it faced significant risks due to its mountainous location and the necessity of relocating roads that intersected with social facilities. In this study, SSM was applied to identify and analyse project risks related to performance, cost and time. Rich Pictures were used to visually represent the problem situation, highlighting how different risks (e.g., material delivery delays and social disruptions) impacted the project. The Root Definition and CATWOE Analysis helped define how the system could be transformed to mitigate these risks. SSM allowed for a holistic assessment of the project's risks, incorporating the viewpoints of different stakeholders and generating practical recommendations for risk mitigation.

Morey *et al.* (2023) explored how emerging technologies, such as autonomous train operations, could be integrated with legacy rail infrastructure. The study aimed to assess whether autonomous trains could increase rail network capacity, operational flexibility and robustness, while considering socio-technical and human factors. The researchers used Brian Wilson's variation of SSM to frame the problem of integrating autonomy into the rail system. Rich Pictures were created to capture the socio-technical interactions within the rail system, and Root Definitions helped clarify how autonomy could be implemented effectively. Conceptual Models were built to explore different pathways for integrating autonomous technology, ultimately guiding stakeholder discussions and developing actionable strategies for real-world implementation.

In addition to the studies discussed, there are several other articles that have employed SSM in their research. Cooper *et al.* (2006) applied SSM in the rail transport sector to develop integrated crime prevention strategies. Putri *et al.* (2022) used SSM to mitigate socio-ecological risks in toll road construction. Finally, Iwashita and Kato (2016) used SSM to develop a local revitalisation model for tourism and agriculture. Being a methodology, the approach makes use of various other systems tools, techniques and concepts. These include Rich Pictures (see 8.3.6), Root Definitions (see 8.3.7), Purposeful Activity Models, Worldviews and Problematical Situations, to name a few. An example of the methodology, along with the various stages, can be seen in Figure 1.

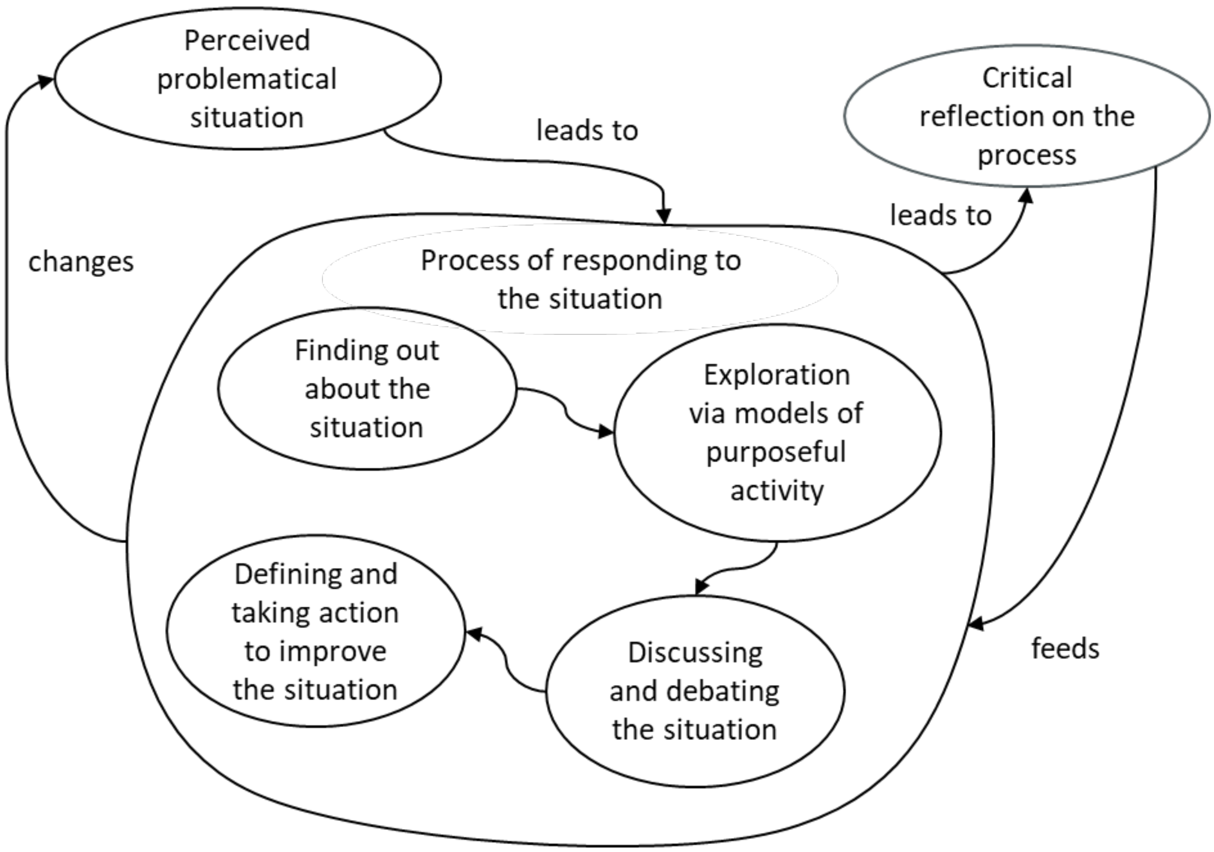


Figure 1: Generalised Soft Systems Methodology (SSM)

8.2.2 Backcasting

Backcasting is an approach used to support the planning and enactment of purposeful activity. It differs from other activity diagramming approaches in that it starts with an imagined possible future situation and then seeks to document the activities or events needed to get there, rather than starting with the current situation and working towards a future situation. This method is particularly useful when dealing with complex societal problems and long-term sustainability goals, where the current path seems inadequate to meet future targets. Key steps in backcasting include:

1 **Defining the desired future state:** This involves setting clear, measurable goals, such as reducing carbon emissions or improving public health outcomes.

2 **Assessing the current system:** The present system is analysed to understand its limitations and the challenges it presents in achieving the desired future.

3 **Identifying external variables:** Key external factors, such as economic growth, technological developments or international regulations, are considered for their influence on both current and future scenarios.

4 **Developing a pathway:** Specific actions and policy measures are identified and mapped backwards from the future state to the present, ensuring that each step is feasible and effective in moving towards the goal.

Figure 2 illustrates a generalised backcasting process, depicting how future goals guide present actions.

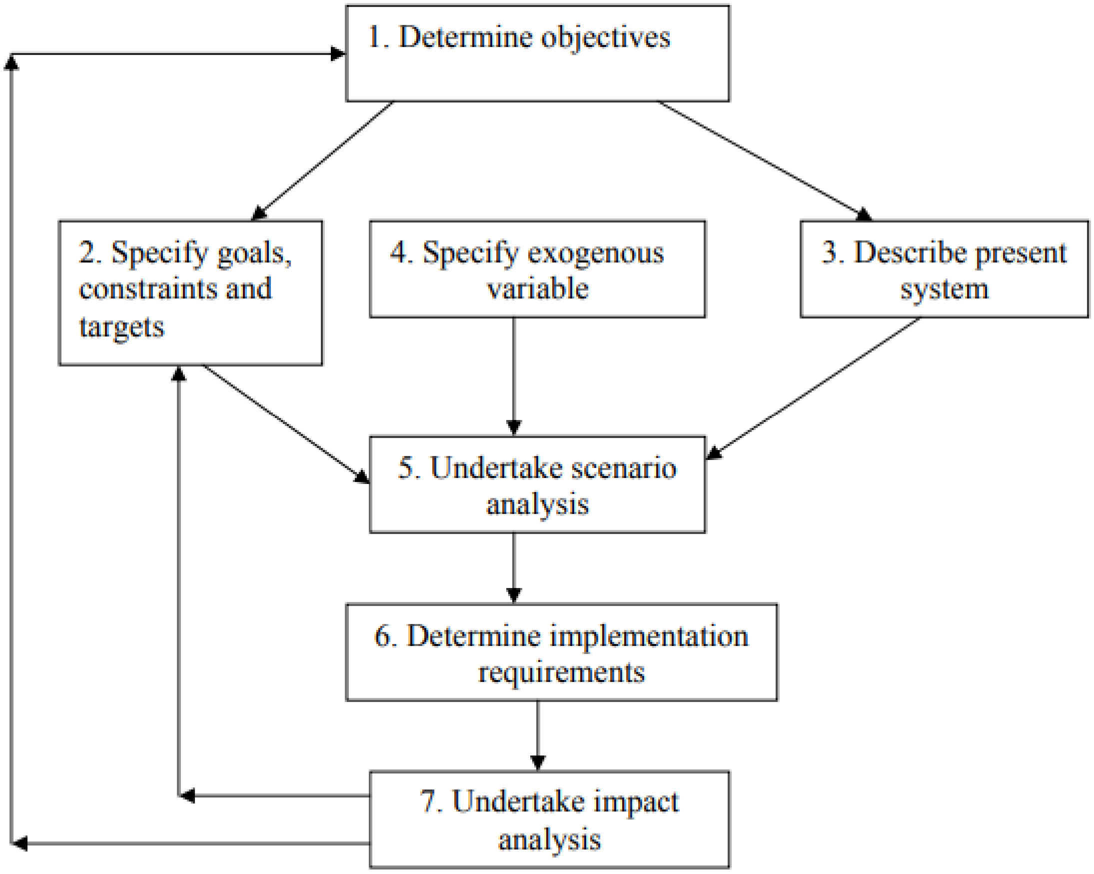


Figure 2: Outline of general backcasting method (Source: Geurs and Van Wee, 2004)

Examples within the transport field include using backcasting to assess the economic feasibility of transport systems and their technical progress towards being environmentally sustainable (Schade and Schade, 2005; Geurs and Van Wee, 2004; and Akerman and Hojer, 2006). For instance, Geurs and Van Wee (2004) used backcasting to explore how the Dutch transport system could meet environmental sustainability targets by 2030. The project set standards for reducing CO2 emissions, nitrogen oxide (NOx), volatile organic compounds (VOC), particulate matter (PM) and noise pollution. The backcasting approach allowed the researchers to work backwards from the desired future, identifying necessary policy instruments, such as improving vehicle technologies, reducing car use and shifting towards public transport and cycling. Key findings indicated that achieving these sustainability goals would require significant technological advances, behavioural changes and new economic structures at both national and international levels.

Similarly, Schade and Schade (2005) used the backcasting approach to develop scenarios for achieving environmentally sustainable transport in Germany. Specifically, they worked backwards from the goal of reducing CO2 emissions by 80% by 2030 and 50% by 2050. In the process, they identified the technical progress, policy strategies and changes in transport behaviour necessary to meet these environmental targets. For instance, they considered higher road transport prices, improvements in vehicle emissions and significant reductions in car usage. These scenarios were assessed for their economic feasibility using the ESCOT model – a System Dynamics Model that evaluates both the short-term and long-term economic impacts of transitioning to a more sustainable transport system.

In Sweden, Akerman and Hojer (2006) focused on developing a sustainable transport system for Sweden by 2050, aiming to reduce energy use per capita by 60% and achieve a 42% reduction in global greenhouse gas emissions. The backcasting approach was central to the study, with researchers identifying necessary steps such as limiting air travel growth, shifting towards cycling and public transport, and improving urban planning to reduce car dependence. One specific outcome was the identification of high-speed rail as a key solution for reducing emissions from domestic air travel. The study also emphasised the need for policy measures, such as carbon pricing and prioritising investments in public transport.

Each of these projects used backcasting to focus on how to meet long-term environmental goals by identifying the necessary changes in technology, policy and societal behaviour.

8.2.3 Boundary Judgements

Within the discipline of systems, the choice of where the boundary of one system or sub-system is drawn and another starts impacts hugely on any assessment of that system. As with many aspects of systems thinking, system boundaries vary depending on the perspective they are observed from.

By exploring Boundary Judgements, practitioners of systems approaches are seeking to reveal diverging judgements as to what aspects of a situation ought to be part of the situation and what aspects ought to be left out (Ulrich and Reynolds, 2010). Their assessment using approaches such as Critical Systems Heuristics (CSH) (see 8.2.4) offers learning opportunities in their own right (Wenger, 2010). This learning highlights the sources of influence over the judgement and allows practitioners to better understand the situation.

8.2.4 Critical Systems Heuristics (CSH)

This is an approach that can be used to formulate and evaluate strategic interventions within complex situations. It is a framework for reflective practice and is intended to support boundary critique, an aspect of Boundary Judgements (see 8.2.3). The approach uses 12 questions to make explicit the everyday judgements that are made to understand situations and to design systems for improving them (Ulrich and Reynolds, 2010).

These questions cover various boundary judgements informing the system of interest (focused around social roles, specific concerns and key problems) along with their sources of influence (including sources of motivation, control, knowledge and legitimacy). The questions often reveal diverging judgements as to what aspects of the situation ought to be or are part of the picture (Ulrich and Reynolds, 2010), or put simply how the situation is framed.

8.2.5 Critical Systems Thinking (CST)

Developed to allow for the analysis of complex societal problems and thus generate interventions to resolve them, Critical Systems Thinking (CST) sets out how the variety of available systems methodologies can be used together in a coherent manner to promote successful interventions (Jackson, 2001).

Inspired by social theory and systems thinking, it seeks to provide a unified approach to problem management. It does this by showing the complementary role the various systems methodologies play in decision-making and problem management, as well as demonstrating the power of systems thinking as a source of theoretical support and practical guidance in the management sciences. In a typical CST approach, the following stages are visualised:

1 **Problem identification:** Acknowledging the need for multiple perspectives.

2 **Methodology selection:** Choosing a mix of systems approaches based on the problem context (hard, soft or critical).

3 **Analysis and implementation:** Using techniques like Critical Systems Heuristics (CSH) and Total Systems Interventions (TSI) to implement solutions. TSI, developed by Mike Jackson and Robert Flood within Critical Systems Thinking (CST), is a meta-methodology designed to help practitioners address complex, conflicting problems by combining multiple systems approaches in a coherent, adaptable way. TSI's three phases are: (a) Creativity: Explore multiple perspectives to capture the problem's complexity, (b) Choice: Select appropriate systems methodologies based on the problem context and stakeholder needs, and (c) Implementation: Apply and adapt methodologies, remaining responsive to new insights. Promoting pluralism, TSI integrates hard, soft and critical systems approaches, while its emancipatory commitment seeks to empower all stakeholders, including marginalised groups, throughout the decision-making process.

4 **Continuous learning and feedback:** Iterating solutions based on insights gathered from stakeholders.

For instance, Khanaum and Hossain (2023) employed CST to handle the complexities of the environmental and social impacts of the Bangladesh gas field blowout, where the incident caused severe damage to local infrastructure, including railway lines that were closed for months; using Critical Systems Heuristics (CSH), the researchers revealed underlying assumptions and boundary judgements in how decisions were made. CST facilitated dialogue among stakeholders, addressing issues like compensation and accountability in the aftermath of the disaster. Jackson (2001) illustrated the broader application of CST, including its relevance to transport policy, through the use of pluralist methodologies tailored to complex problem situations. His approach draws from both social theory and systems thinking to offer a unified framework for managing complex issues. CST critiques traditional systems approaches, such as operational research and systems engineering, by highlighting their limitations when addressing problems that involve human subjectivity and conflict.

Jackson advocates for a pluralist approach, where different systems methodologies are applied based on the specific context, enabling a more flexible and holistic intervention. His work also focuses on ensuring that systems thinking provides both theoretical support and practical guidance in addressing societal and organisational challenges.

8.2.6 Stakeholder Analysis

Within the discipline of systems thinking there are various approaches for undertaking Stakeholder Analysis. Regardless of their differences, all of these approaches seek to identify and obtain information associated with stakeholders within the situation of interest. This information allows practitioners to better understand the situation they are seeking to change.

The simplest approach to Stakeholder Analysis, and often the first used, is a mapping exercise to identify individuals or groups who may have an interest in, or are affected by, the situation under investigation. Typically, practitioners will make use of their existing knowledge of the situation to do this. Those stakeholders identified are often categorised according to defined criteria (e.g., level of interest). Practitioners can then utilise the mapping outputs to further engage with or gather information on the various stakeholders.

Another way of undertaking Stakeholder Analysis is to develop a stakeholder map from a direct enquiry of the situation of interest. This can be achieved by formulating an enriched Root Definition (see 8.3.7) and assuming those individuals or groups identified are stakeholders for the situation of interest. The enriching process sees the practitioner identify various parties in accordance with the mnemonic CATWOE (Customers, Actors, Transformation process, Worldview, Owners and Environmental constraints):

- **Customers:** Parties that may benefit from or suffer due to the transformation.
- **Actors:** Individuals or groups undertaking transformation activities.
- **Transformation process:** The process by which the transformation occurs.
- **Worldview:** The values, beliefs and priorities that underly the transformation.
- **Owners:** Those with the authority to halt the transformation.
- **Environmental constraints:** External factors influencing the situation.

Alternative enquiry of the situation can be achieved via the investigation of Boundary Judgements (see 8.2.3) and the critiquing technique within Critical Systems Heuristics (CSH). Similar to the enriching processes for Root Definitions, CSH sees practitioners identify various groups (beneficiaries, decision-makers, experts, guarantors and witnesses), with those individuals or groups identified in these roles being stakeholders for the situation of interest.

Various examples of Stakeholder Analysis were identified as part of the review. These showed instances of its application across most of the transport modes, be that within the roads (Katopola *et al.*, 2024) or rail (Kordnejad, 2016) sectors. Katopola *et al.* (2024) conducted a comprehensive Stakeholder Analysis of the road transport system in Tanzania using the STAMP (Systems-Theoretic Accident Model and Processes) control structure. The authors identified various stakeholder roles and relationships, focusing on control and feedback mechanisms that influence road safety. Their findings underscore the complexity of the road transport system and highlight gaps that need addressing to enhance safety.

Kordnejad (2016) evaluated stakeholder perspectives on intermodal urban freight transport. By employing the Delphi Method (see 8.2.7), the study gathered insights from various stakeholders on their preferences and concerns about adopting rail-based intermodal transport solutions in urban areas. Floden and Woxenius (2021) analysed stakeholders involved in the land transport of dangerous goods. The authors mapped out the relationships among stakeholders, including shippers, transport providers, regulatory authorities and local communities, to enhance safety in dangerous goods transport. Their research emphasises the importance of stakeholder engagement for risk management and safety improvements.

Węgrzyn and Wojewnik-Filipkowska (2022) focused on stakeholder analysis in the context of public–private partnerships (PPPs) for infrastructure projects. The authors identified different stakeholder groups and their attitudes towards the success of PPPs, highlighting the significance of stakeholder engagement for sustainable infrastructure development.

Veitch *et al.* (2020) discusses the importance of stakeholder analysis for the design of shore control centres for autonomous ships. The authors identified the roles and influences of various stakeholders involved in the implementation of autonomous shipping technologies, illustrating how effective stakeholder engagement can enhance operational safety.

8.2.7 Delphi Method

The Delphi Method is an approach used to elicit information and opinions from participants to assist in planning and decision-making. This technique is beneficial in complex areas, such as transport systems, where expert consensus is important. The approach involves participants (either experts in the topic or those directly involved in the issue) completing a series of questionnaires. A moderator or facilitator uses the responses from one round of questionnaires (typically starting with broad, open-ended questions) to develop subsequent questionnaires. Key steps in the Delphi Method include:

1 **Defining the objective:** Clearly articulating the purpose of the study, such as identifying research priorities or evaluating the feasibility of new technologies.

2 **Selecting participants:** Involving a diverse panel of experts to ensure a broad range of perspectives. The literature suggests that a panel size of 10–18 is typical, but larger

groups may be used for complex topics, as demonstrated in recent studies involving 30 experts.

3 **Conducting the rounds:** The first round typically contains open-ended questions to gather initial thoughts. Subsequent rounds refine these inputs, allowing participants to reassess their opinions based on the group's feedback.

Figure 3 illustrates the iterative process of the Delphi Method, highlighting how expert feedback shapes successive rounds of inquiry.

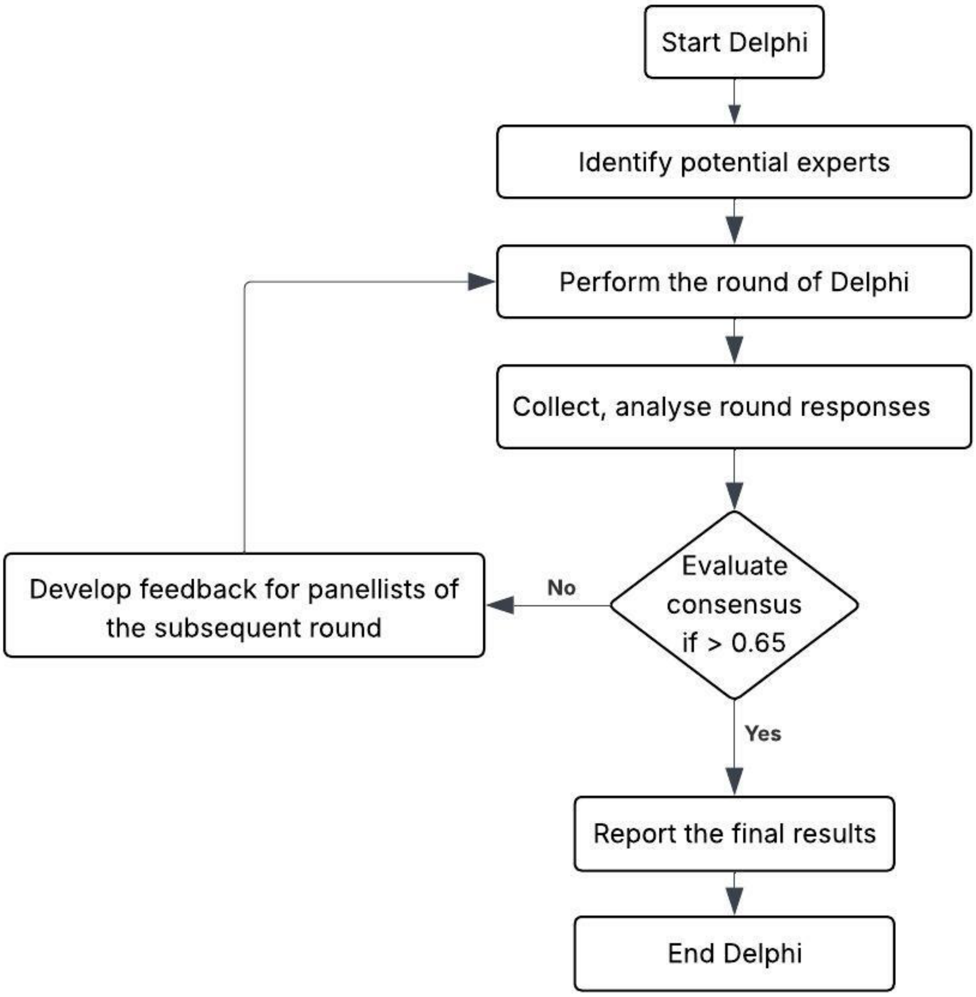


Figure 3: Delphi Method flow chart

There is extensive evidence of how the Delphi Method has been applied within the various transport modes. For example, Pant *et al.* (2022) used the Delphi Method to gather and prioritise research needs for improving road safety in Nepal. The researchers began by conducting interviews with stakeholders from various fields, including government, healthcare, academia and civil society, to identify knowledge gaps. Over two rounds of questionnaires, participants ranked the importance of 1,019 research suggestions, which were clustered and condensed into key research questions. The technique facilitated a consensus on the most urgent road safety research needs, including vehicle fitness, driver licensing and public vehicle crash prevention. The Delphi Method was valuable in ensuring input from a broad range of experts and achieving consensus on prioritising research areas.

Djordjevic *et al.* (2023) used a combination of Delphi and Analytic Network Process (ANP) methods to investigate the determinants of deploying autonomous train operations (ATO) in freight rail. The Delphi Method was applied in the early stages to collect expert opinions on the challenges, risks, benefits and critical subsystems of ATO. The responses from the first round of open-ended questionnaires helped identify the key determinants necessary for ATO deployment. The results were then used to prioritise these determinants using the ANP method. The Delphi Method ensured that expert knowledge and judgement were systematically incorporated into the decision-making process, particularly when identifying the most viable automation grades for freight trains.

Similarly, a study by Cafiso *et al.* (2013) utilised the Delphi Method to evaluate the opinions of public transport managers on bus safety. By employing a multi-round Delphi process, the researchers achieved consensus on key safety improvements such as start inhibition and automatic door opening. The findings indicated that specific technologies, such as vehicle monitoring systems, were deemed critical for enhancing bus safety standards.

Other transport systems like rail have used this method as well. For example, a study by Kordnejad (2016) aimed to evaluate the feasibility of rail-based intermodal transportation in urban regions using a Delphi-like approach. Experts participated in workshops and surveys to assess stakeholder perspectives on and barriers to utilising intermodal transport systems. The study underscored the importance of aligning transportation solutions with local authority policy objectives to enhance feasibility.

In aviation, Efthymiou and Papatheodorou (2018) used the Delphi Method to inform environmental considerations within the Single European Sky programme, and Linz (2012) used the Delphi Method to develop future scenarios for the industry. In maritime transport, Arof (2015) evaluated the integration of Delphi and Analytic Hierarchy Process (AHP) methods, and in intermodal and urban freight transport, Delphi has assisted in stakeholder analysis for intermodal systems by Kordnejad (2016).

8.2.8 Socio-Technical Systems Theory (STS)

Socio-Technical Systems Theory (STS) concerns the design of organisations (or systems) that comprise technical and social components (Hadid *et al.*, 2016). It concerns the technical factors, individuals' social relationships and organisational factors within an organisation (Kuo and Chen, 2021). Its primary principles are that the interaction of social and technical aspects within an organisation inform performance, and that optimisation of either social or technical aspects alone typically negatively impacts organisational performance.

The STS approach integrates various dimensions of an organisation, examining technical factors, social relationships among individuals and organisational structures, shown in Figure 4. By analysing how these elements interact, the STS framework can guide the design and optimisation of complex systems to improve overall effectiveness and adaptability. Key components of the STS method include:

1 **Identifying components:** Recognising both social (people, relationships) and technical (processes, tools) elements within the organisation.

2 **Evaluating interactions:** Understanding how the technical and social components influence one another.

3 **Designing for integration:** Creating systems that support harmonious interactions between social and technical elements to enhance performance.

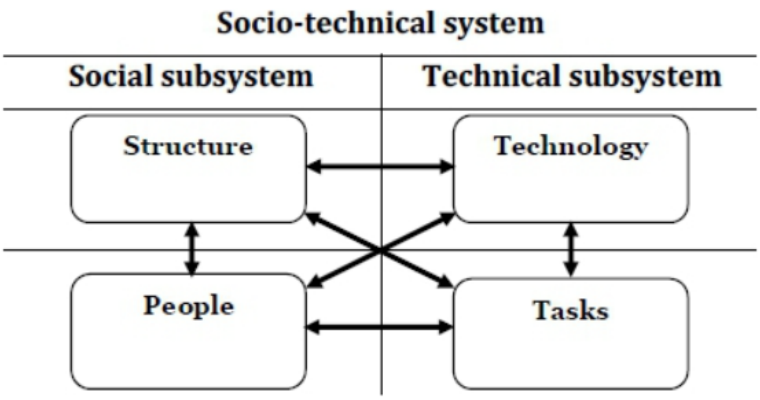


Figure 4: Socio-Technical Systems (STS)

The approach appears to have been applied in various transport industries. There is some evidence of its use to examine the requirements for future services (Relling *et al.*, 2019) and to assess the benefits of changing practice for container shipping (Kuo and Chen, 2021). In detail, Relling *et al.* (2019) employed STS theory to explore the future of Vessel Traffic Services (VTS) in the maritime industry. The authors argue for a proactive approach in evaluating the implications of autonomy on VTS and propose a systemic evaluation of internal and external consequences. The findings highlight the importance of integrating diverse competencies and perspectives in the early design phase of VTS to adapt to future changes in maritime operations. Also, Kuo and Chen (2021) examined the relationship between lean management practices and operational performance in the context of container shipping. By applying STS theory, they demonstrate how lean practices can enhance both social and technical dimensions, leading to improved performance outcomes. Their findings underscore the need for organisations to address both social and technical aspects for achieving sustainable operational improvements.

Heidi *et al.* (2014) discuss the application of STS theory in various industries, outlining how the integration of technical and social systems can lead to enhanced organisational performance. The authors provide case studies that illustrate the practical implications of applying STS principles in real-world scenarios, emphasising the need for a holistic approach to organisational design.

Pence *et al.* (2014) integrated STS theory with probabilistic risk assessment to develop a framework for monitoring organisational safety indicators. By addressing the interplay between organisational factors and technical systems, the study provides insights into how STS theory can enhance safety management practices within high-risk environments.

Alternative enquiry of the situation can be achieved via the investigation of Boundary Judgements (see 8.2.3) and the critiquing technique within Critical Systems Heuristics (CSH). Similar to the enriching processes for Root Definitions, CSH sees practitioners identify various groups (beneficiaries, decision-makers, experts, guarantors and witnesses), with those individuals or groups identified in these roles being stakeholders for the situation of interest.

8.2.9 Strategic Options Development and Analysis (SODA)

SODA is an approach that facilitates the exploration of options, and their ramifications, with respect to problematical situations. It is based upon the use of cognitive and causal mapping, a formally constructed means–ends network, and aims to assist a group in learning about the situation they face before reaching agreement on action (Ackermann and Eden, 2010). The SODA process encourages participative decision-making and collective understanding, making it particularly effective for addressing multifaceted challenges. The SODA methodology involves several key components:

- **Cognitive mapping:** This process entails creating a visual representation of the stakeholders' mental models of a particular situation. It helps identify the relationships and causal links between different factors that influence the problem.
- **Causal mapping:** This aspect focuses on establishing cause-and-effect relationships within the system, enabling practitioners to see how various components interact and influence each other.
- **Means–ends network:** SODA employs a structured approach to define the means (resources and actions) necessary to achieve desired ends (goals and outcomes). This network provides clarity on how specific options can lead to the intended results.

An example of a cognitive or causal map can be seen in Figure 5.

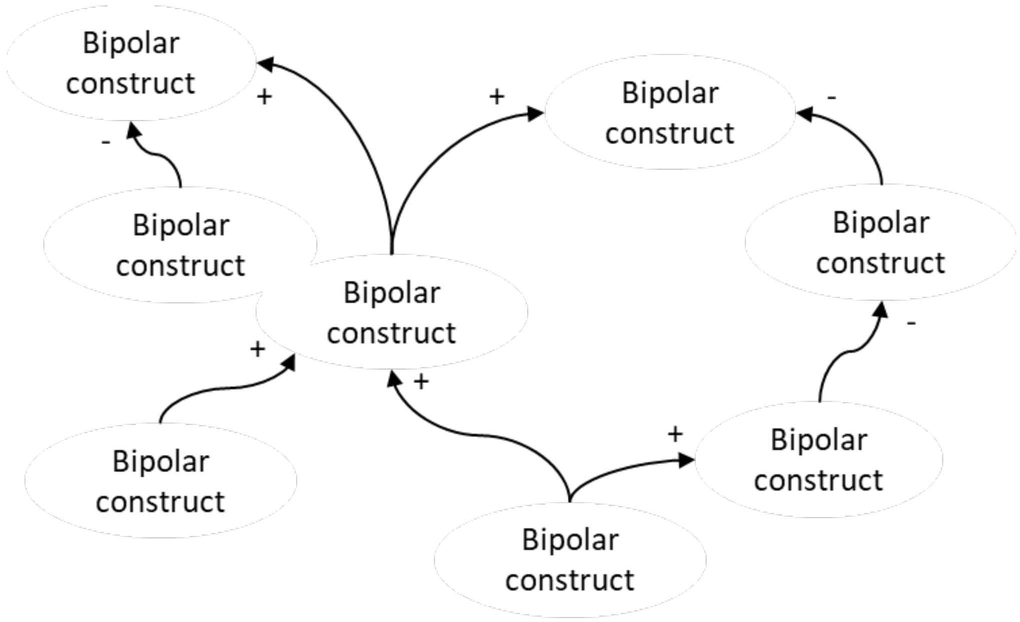


Figure 5: Generalised cognitive/causal map

The approach has benefited from advances in technology, with mapping software enabling maps to be viewed and amended by groups or individuals (ensuring complexity is maintained rather than being reduced) as well as facilitating rapid analysis.

The cognitive mapping aspects of SODA have been utilised within various transport planning activities. This investigation found examples of the technique being used to inform accident prevention strategies within the maritime mode (Akyuz and Celik, 2014), along with informing the prioritisation of road infrastructure investments in an attempt to address mobility challenges (Vajjhala and Walker, 2010). Akyuz and Celik (2014) utilised cognitive mapping to model human error in marine accident analysis and prevention. By mapping the cognitive perceptions of stakeholders, the authors identified key factors contributing to maritime accidents and proposed strategies for improvement. Their findings highlight the effectiveness of cognitive mapping in enhancing safety and reducing human error in maritime operations. Vajjhala and Walker (2010) discuss the integration of cognitive mapping and GIS to inform the prioritisation of road infrastructure investments in rural Lesotho. The authors employed SODA to explore the various factors influencing transport challenges and the potential impacts of different investment strategies. Their work illustrates the value of participatory planning in addressing mobility issues through informed decision-making.

8.2.10 Failure Modes and Effects Analysis (FMEA)

FMEA is an approach for identifying potential failure modes in a system, along with their causes and effects. It can be used as part of an investigation into a system failure, or as pre-emptive action in order to stop it taking place. While traditionally used for hard or engineering systems, such as identifying technical faults in vehicles or infrastructure, it can also be adapted for soft or social systems, such as analysing communication breakdowns or organisational process failures. This flexibility allows FMEA to address both technical and social aspects of transport safety, making it a valuable tool for investigating systemic failures or taking pre-emptive actions to prevent them. The flow chart in Figure 6 shows that FMEA involves a structured analysis process that typically includes the following steps:

1. **Identifying the system components:** Break down the system into its individual components or processes.
2. **Listing potential failure modes:** For each component, identify possible failure modes and how they can occur.
3. **Assessing the effects of failures:** Evaluate the potential impact of each failure mode on the system's performance and safety.
4. **Determining severity, occurrence and detection ratings:** Assign ratings for the severity of effects, the likelihood of occurrence and the ability to detect the failure before it happens.
5. **Calculating Risk Priority Numbers (RPN):** Calculate the RPN by multiplying the severity, occurrence and detection ratings, providing a quantitative measure to prioritise risks.
6. **Identifying corrective actions:** Based on the RPN, suggest actions to mitigate the identified risks.

FMEA serves as a foundational tool for risk management in various industries, enhancing the reliability and safety of complex systems.

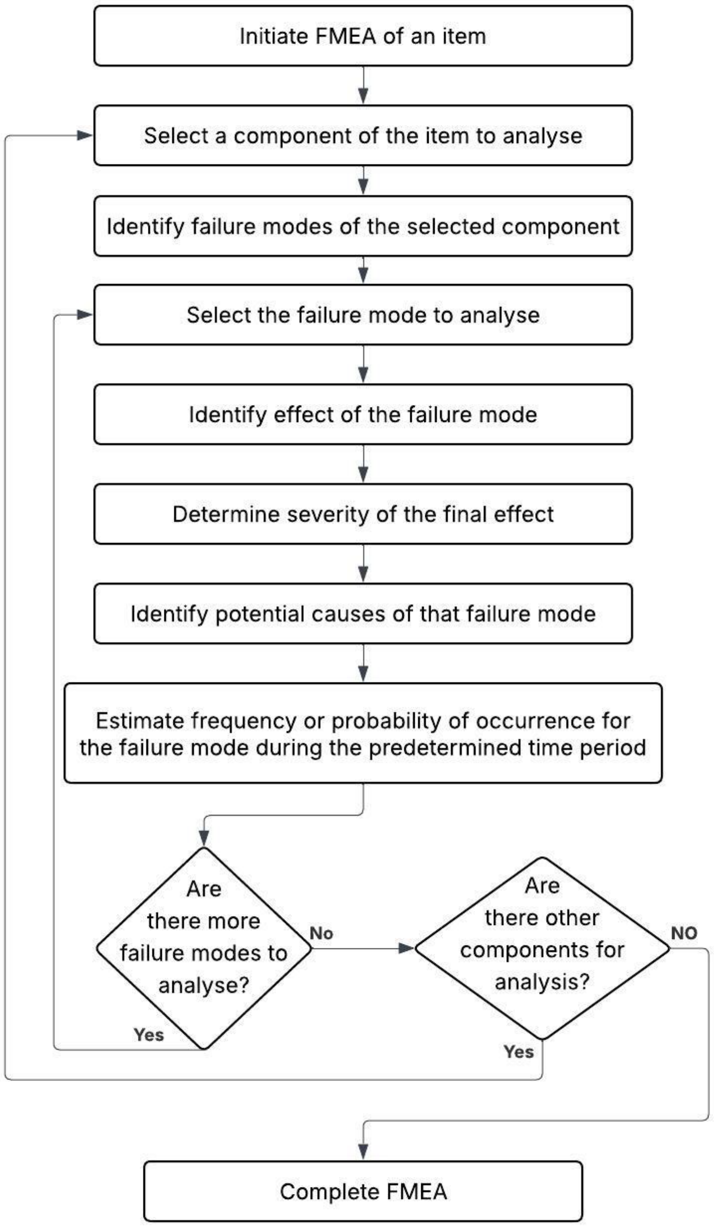


Figure 6: Failure Modes and Effects Analysis

This investigation found evidence of the approach being used within all transport sectors. It has been used to assess specific aspects of systems failure, such as crankcase explosions (Cicek and Celik, 2013), and the broader reliability of systems, such as high-speed rail (Rakhmetova *et al.*, 2018) and in aviation (Milner and Ochieng, 2008).

For instance, Cicek and Celik (2013) discuss the application of FMEA in marine engineering to analyse crankcase explosions in marine diesel engines. The study highlights how FMEA can improve machinery system reliability and operational safety by identifying potential failure modes associated with crankcase operations. The authors propose a framework for integrating innovative technologies and operational practices to reduce the occurrence of such failures. The findings suggest that adopting these measures can enhance safety and reliability within the marine sector.

Rakhmetova *et al.* (2018) focused on the reliability evaluation of high-speed railway traction systems using FMEA. The authors employed the TARAS software to conduct a detailed analysis of the traction system components, identifying the most vulnerable elements, such as traction system motors. Their analysis resulted in a calculated failure rate, enabling the formulation of recommendations for improving performance efficiency and reliability in high-speed rail systems. The study illustrates the effectiveness of FMEA in assessing and enhancing the reliability of complex transport systems.

Zhou and Thai (2016) introduced a fuzzy approach to FMEA, applied to tanker equipment failure prediction. They integrated fuzzy and grey theories to evaluate risk factors associated with equipment failures, allowing for a more nuanced analysis compared with traditional FMEA. This approach enhances decision-making on inspection and maintenance schedules, ultimately contributing to safer and more reliable tanker operations. The findings demonstrate the applicability of fuzzy FMEA in improving the reliability of critical equipment in maritime transport.

Savelev *et al.* (2021) discuss the development of a model-based approach to FMEA, focusing on enhancing the safety assessment of aircraft systems. By employing tools like ANSYS Medini Analyze, the authors aimed to minimise human errors in the FMEA process. The findings indicate that using model-based methods can improve the identification of failure modes and enhance overall system safety in aviation applications.

Overall, FMEA is an essential tool that has been effectively applied across various transport sectors, aiding in the identification and mitigation of potential failures to enhance system reliability and safety.

8.2.11 SWOT Analysis

A Strengths, Weaknesses, Opportunities and Threats (SWOT) Analysis is an approach used to support or evaluate a decision-making process. The approach can have variants; for example, threats can be replaced with challenges and actions, better known as SWOCA.

The approach seeks to elicit and capture participants' thoughts on an intervention, grouping them by the previously mentioned categories. The components of a SWOT Analysis, as can be seen in the Table 3, include:

- **Strengths:** Internal attributes or resources that enhance the ability to achieve objectives.
- **Weaknesses:** Internal limitations or deficiencies that hinder progress.
- **Opportunities:** External factors that can be leveraged to advantage the organisation.
- **Threats:** External challenges or obstacles that could jeopardise success.

Table 3: Generalised SWOT Analysis

Strengths	Weaknesses	Opportunities	Threats
Thoughts	Thoughts	Thoughts	Thoughts
Thoughts	Thoughts	Thoughts	Thoughts

Being such an established approach, examples of its application can be found across all modes of transportation. Examples of its use can be seen in documented efforts to assess aviation strategies associated with low carbon and environmental protection (Feng *et al.*, 2019), as well as decision-making efforts associated with selecting rail and road terminals (Stoilova and Martinov, 2019). Feng *et al.* (2019) employed SWOT Analysis to assess aviation strategies associated with low carbon and environmental protection in Jilin Province, China. The authors identified strengths such as sustainable economic foundations and opportunities related to rising e-commerce demand, while also noting weaknesses in cargo capacity and threats from increasing competition. Similarly, Stoilova and Martinov (2019) used a hybrid SWOT and Multi-Criteria Decision-Making (MCDM) model to select a location for establishing a rail and road intermodal terminal. The SWOT Analysis identified critical strengths, weaknesses, opportunities and threats related to potential terminal sites, facilitating informed decision-making about terminal placement.

The SWOT Analysis method has also been applied in other studies, including developing strategies for reducing the risks associated with hazardous materials transportation in Iran (Kheirkhah *et al.*, 2009), evaluating the air cargo sector's situation in the context of the COVID-19 pandemic (Li, 2020) and assessing intermodal rail freight transport in Belgium (Torch *et al.*, 2015).

8.2.12 System Dynamics

System Dynamics, which retains the fundamental aspects developed in the 1950s, focuses on the relationship between dynamic behaviour and feedback loop structures (Morecroft, 2010). It looks at how these feedback loops and time delays affect system performance in a non-linear way. Key components of System Dynamics include:

- **Feedback loops:** Core elements illustrating how outputs of a system feed back into the system as inputs, influencing future behaviour.
- **Causal Loop Diagrams (CLDs):** Visual tools that map the causal relationships among different variables in a system, helping to identify reinforcing and balancing loops.
- **Time delays:** Recognising the delays that can occur in feedback loops, which significantly impact the dynamics of a system and its performance.

These concepts are frequently illustrated using CLDs, an example of which can be seen in Figure 7.

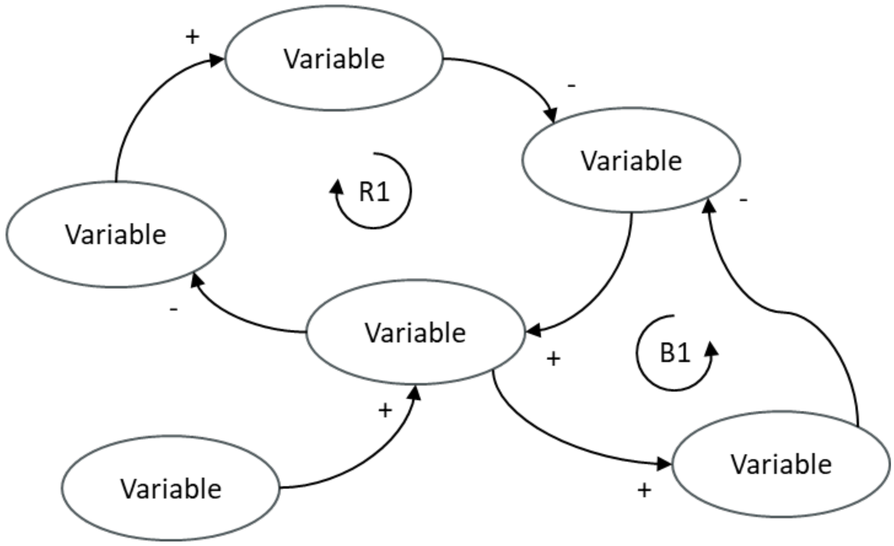


Figure 7: Generalised Causal Loop Diagram

System Dynamics is able to focus in on cause and effect between factors, and there is extensive evidence that it has been used to model problematical situations and possible changes across all the core transport modes (aviation, maritime, rail and road). For example, the approach was used to understand safety concerns associated with the operation of motorcycle taxi drivers, a particularly vulnerable group in terms of road safety, generating insights into breaking undesirable behaviours (Aluko *et al.*, 2011).

It has also been used to assess the impact of one transport system on another, for example an urban rail system and road system, as well as the broader impacts of the chosen transport system on the local economy, society and environment (Yang *et al.*, 2014).

More recent efforts have seen the approach being used in conjunction with a computer program leveraging large language models to automate the creation of CLDs (Hosseinicheimeh *et al.*, 2024).

Other studies that have used the technique include Rosales *et al.* (2014), who analysed delays in aircraft heavy maintenance, and Motawa *et al.* (2013), who developed a demand forecasting model for public–private partnership toll road projects. Studies such as Gupta *et al.* (2019) and Tolujevs *et al.* (2018) have also applied System Dynamics to various transport-related issues, including carbon taxation, demand forecasting in toll road projects, and road transport enterprise performance, often using multiple techniques together to enhance their analyses.

8.2.13 Viable System Model

Developed by Stafford Beer in the early 1970s, this conceptual model seeks to demonstrate how organisations create viability (Hoverstadt, 2010). Organisations – in the context of this report – can be taken to mean human activity systems. However, it is not just a model of organisations plural but also a model of organisation and thus relevant to other domains. For example, in his early work Beer used the model to map the human nervous system. Viability in this model means the capacity to exist and thrive in sometimes unpredictable and turbulent environments. The model is used by practitioners in two ways: firstly as a diagnostic tool for comparison against actual systems, and secondly as an ideal type structure for the purpose of designing new systems.

Often presented as a graphical representation of a system (see Figure 8), the model captures a number of critical components and connections needed for viability. These components include various subsystems (operations, coordination, delivery, development and policy) as well as the environment within which the system is located. Importantly the model illustrates the various critical interrelationships needed between components.

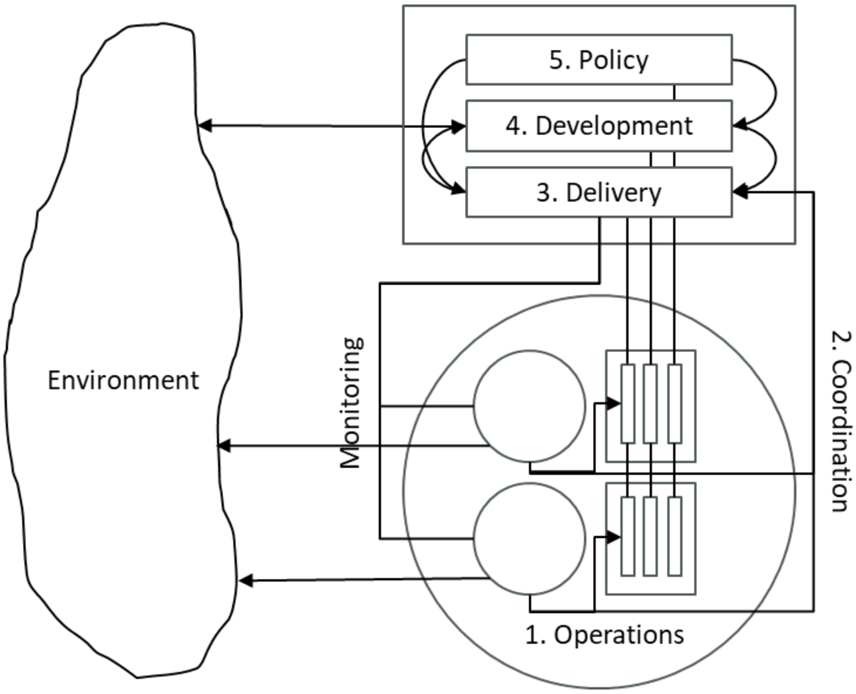


Figure 8: Generalised Viable System Model

8.3 Communication tools used in systems thinking

There are a variety of tools that are commonly used to help communicate systems thinking ideas. This section provides a description of a range of systems thinking communication tools that have been used in the transport sector.

8.3.1 Activity Sequence Diagrams

Used to define a sequence of activities over time, these diagrams are made up of boxes (representing the commencement or completion of an activity or event) linked by arrows (indicating the logical sequence of the related activities) that indicate the passage of time. Typical conventions see the earliest activities positioned to the left of the diagram, along with numbering the sequence of activities.

An example of such a diagram can be seen in Figure 9.

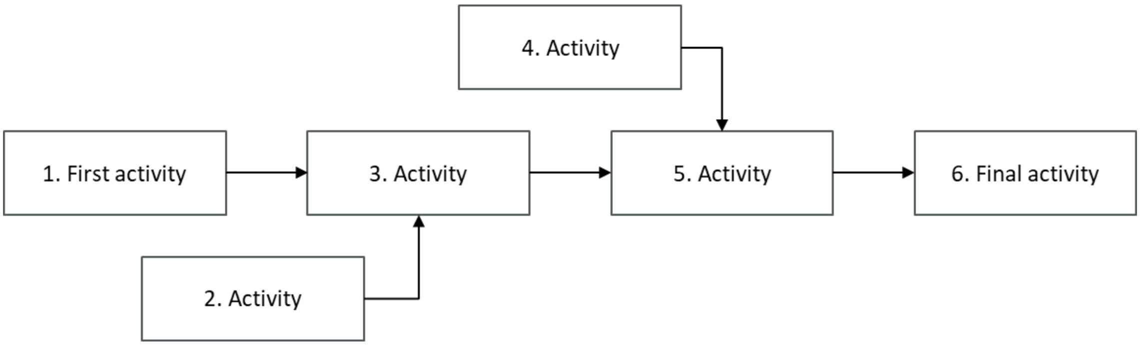


Figure 9: Generalised Activity Sequence Diagram

As the diagramming approach helps define processes or activity, its use is applicable in support of many other systems tools listed within this report, such as Soft Systems Methodology (see 8.2.1) and Systems Dynamics (see 8.2.12). The approach does not require specialist knowledge or software to implement and is already commonly used by project managers in all types of industries.

As with all systems diagramming approaches, documenting the activity in a diagrammatic form aids practitioners in the process of understanding complex situations. However, it is framed as a snapshot from a defined perspective – that of the individual or group who constructed the diagram at a specific time.

8.3.2 Conceptual Modelling

Used to represent purposeful activity systems within Soft Systems Methodology (see 8.2.1), Conceptual Models are similar in appearance and construction to Activity Sequence Diagrams (Section 8.3.1) but are derived from Root Definitions (see 8.3.7). This is achieved through a process of determining the actions implied by or contained within the Root Definition and then organising them into a logical sequence.

The Viable System Model (see 8.2.13) is an example of a Conceptual Model (Hoverstadt, 2010). A more general Conceptual Model can be seen in Figure 10.

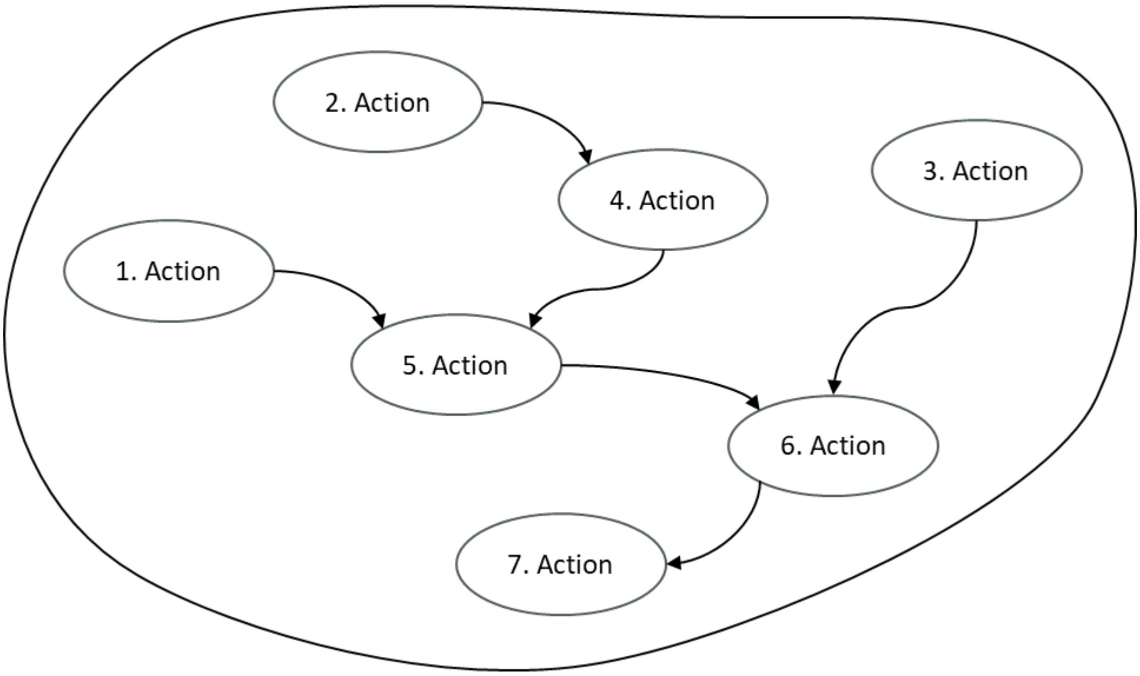


Figure 10: Generalised Conceptual Model Diagram

8.3.3 Control Model Diagrams

Originating in control engineering as an aid to designing and constructing complicated machinery, Control Models have been adapted over time for use in many non-engineering activities. The diagrams indicate the regulation process within a system that ensures an objective or standard is achieved.

Such diagrams typically contain a box representing the transformation process, associated input and output arrows, a circle representing a sensor (which gathers information from the outputs of the transformation comparable with the intended objective or standard), and a feedback loop leading to the comparator and then onto an actuator within the process inputs. All of these aspects are intended to simplify the regulatory process.

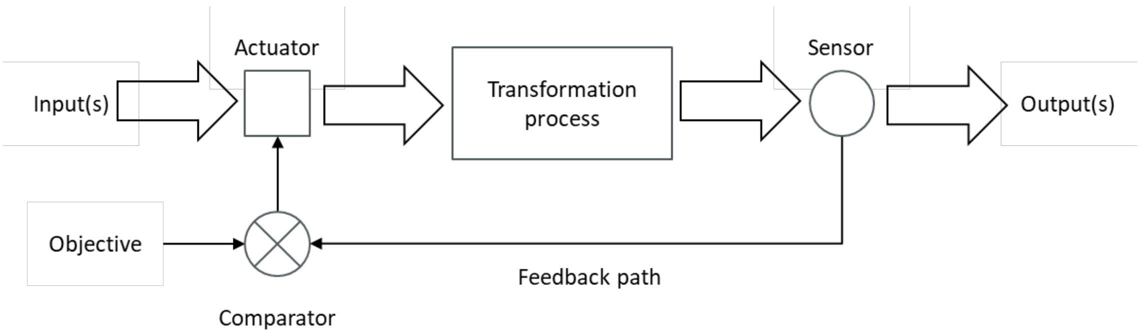


Figure 11: Generalised Control Model Diagram

8.3.4 Influence Diagrams

Influence diagrams are graphical representations of a decision situation. The diagram depicts decisions, uncertainties and values each connected using various arcs (functional, conditional and informational). This method allows for a visual representation of how different elements interact within a decision-making framework. Key components of Influence Diagrams include:

- **Decision nodes:** Representing the choices available to decision-makers.
- **Chance nodes:** Indicating uncertainties that may influence the outcomes.
- **Value nodes:** Reflecting the value or utility associated with different outcomes.
- **Arcs:** Connecting the nodes, illustrating the relationships between decisions, uncertainties and values.

An example of an Influence Diagram can be seen in Figure 12.

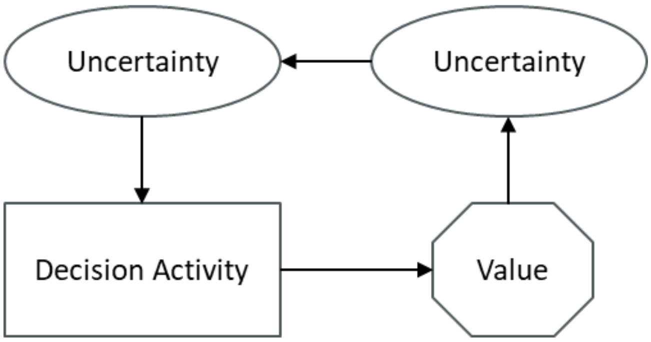


Figure 12: Generalised Influence Diagram

The technique has been used to understand system failures and disruption caused by weather events in both the aviation (Rashid *et al.*, 2015) and maritime (Tian *et al.*, 2024) transport modes respectively. These types of diagrams can be developed from a System Map (see 8.3.9) and can be used as a starting point for a Multiple Cause Diagram (see 8.3.5). For instance, Rashid *et al.* (2015) utilised Influence Diagrams to analyse helicopter main gearbox (MGB) lubrication system failures, integrating random failure probabilities to map potential causes and outcomes. Tian *et al.* (2024) combined Influence Diagrams with physics-based modelling to assess disruptions in seaports caused by tropical cyclones, providing a framework for understanding how various factors interact during extreme weather events.

8.3.5 Multiple Cause Diagrams

Used to explore, in a general sense, the cause of a change within a situation, Multiple Cause Diagrams seek to depict the relevant factors causing the change. They are used by practitioners to develop their understanding of the ways in which aspects of a situation may change or be changed. They typically place the change to be explained in the centre of the diagram, with the various relevant factors arranged outwards.

Causal connections are shown via the use of arrows, with the head of the arrow indicating the resulting effect from the causes located at the arrow's tail. An example of a Multiple Cause Diagram can be seen in Figure 13.

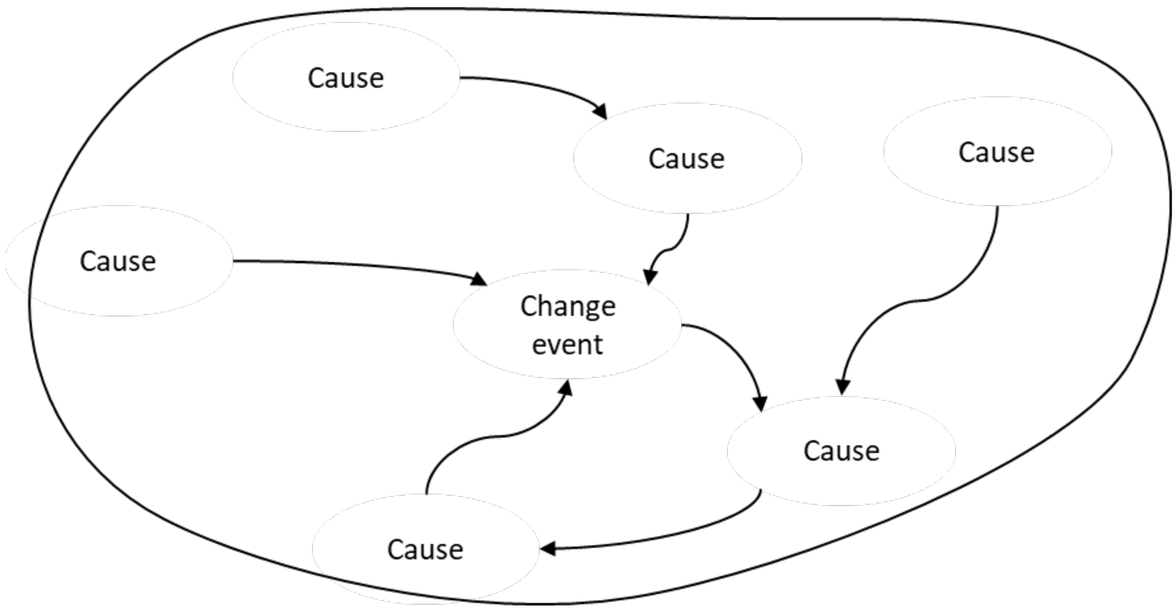


Figure 13: Generalised Multiple Cause Diagram

8.3.6 Rich Pictures

When practitioners attempt to find out about problematical situations, the first activity within Soft Systems Methodology (see 8.2.1), they often turn to making Rich Pictures. In doing so, the aim is to capture, informally, the main entities, structures and viewpoints in the situation, the processes going on, the current recognised issues and any potential issues (Checkland and Poulter, 2010). Key components of Rich Pictures include:

- **Entities:** Major stakeholders or elements involved in the situation.
- **Processes:** The activities or interactions occurring within the system.
- **Issues:** Current recognised challenges and potential future problems.
- **Viewpoints:** Different perspectives from stakeholders involved in the situation.

The technique makes use of a combination of drawings, pictures, symbols and text that represent a particular situation from the viewpoint of the people who drew it. They can be regarded as a pictorial summary of the situation at a given time. This investigation identified published evidence of their use across various transport modes, often in support of the application of Soft Systems Methodology and the development of Conceptual Models. One example saw the technique utilised to support the evaluation of intermodal terminal networks (Floden, 2010). The author applied Rich Pictures to evaluate intermodal terminal networks, focusing on how various stakeholders, including terminal operators, transport companies and customers, interact within the logistics framework. These visualisations effectively captured network complexities and key issues affecting terminal performance, enhancing stakeholder understanding and highlighting the importance of collaboration to improve intermodal transport operations. The Rich Pictures effectively illustrated the complexities of the network, capturing key entities, processes and issues impacting terminal performance and efficiency. By engaging stakeholders in the creation and discussion of these visualisations, Floden's study facilitated a deeper understanding of the challenges faced in intermodal transport and identified potential areas for improvement. The findings underscore the importance of collaboration and communication among stakeholders in enhancing the operational effectiveness of intermodal terminals.

Other studies, such as those by Morey *et al.* (2023) and Lembani *et al.* (2018), have also used Rich Pictures as part of their analyses to frame complex problem situations and engage stakeholders effectively in understanding and resolving issues.

8.3.7 Root Definitions

In order to construct models of a purposeful activity system required within Soft Systems Methodology (see 8.2.1), a statement describing the system is required. Such statements are known as Root Definitions. They describe the purposeful activity as a transformation process, viewed through a perspective relevant to the investigation (Checkland and Poulter, 2010). Specific guidelines exist for creating such descriptions, which see them take shape and then become enriched to help build the purposeful activity model.

8.3.8 Spray Diagramming

This is a diagramming technique that shows the connections between related elements or concepts associated with a particular issue, and it is used in many disciplines. Sometimes referred to as mind maps, the technique is very simple. It consists of lines and ideas expressed in a few words, with the lines indicating association but not the nature of the connection. An example of a Spray Diagram can be seen in Figure 14.

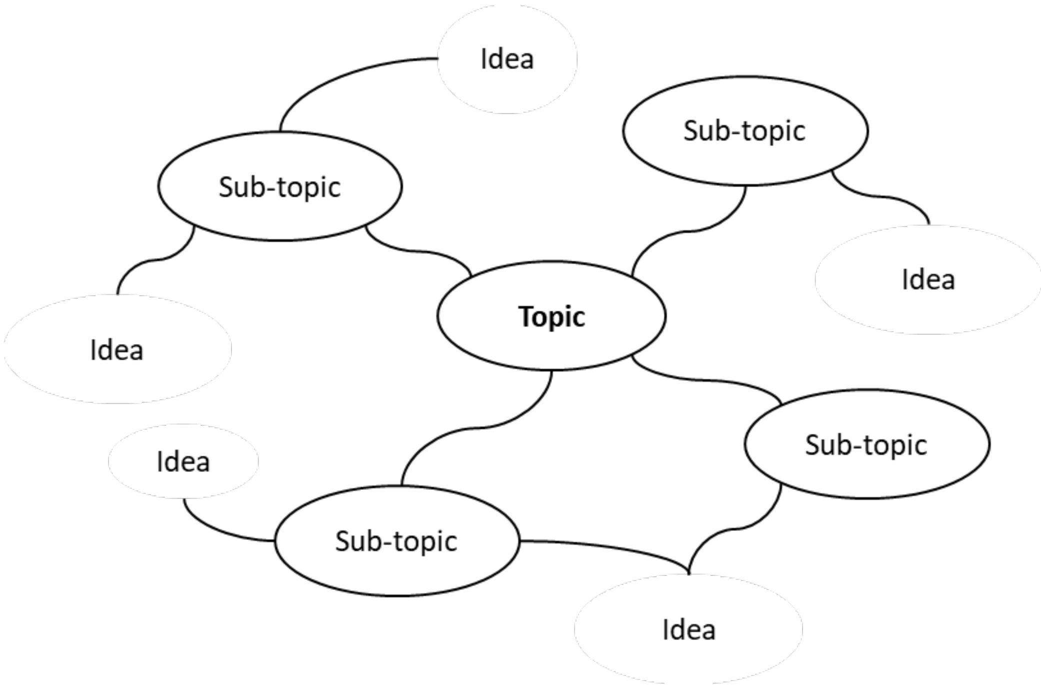


Figure 14: Generalised Spray Diagram

8.3.9 Systems Maps

Like many of the other diagramming techniques presented here, Systems Maps are a snapshot of a situation at a moment in time from an explicit perspective. They seek to capture components of a system along with its environment. Given they are from explicit perspectives it is possible to have different Systems Maps depicting the same situation.

Typically, such diagrams are used to help practitioners decide how they are going to structure the information they have available on a situation, as well as how they wish to document that information and communicate that with others. They are helpful when seeking to explore Boundary Judgements (see 8.2.3).

The technique follows a loose set of conventions, with elements or components of a system depicted within a circle, the system boundary depicted by an encompassing border, with environmental components placed outside the system boundary. An example of a Systems Map can be seen in Figure 15.

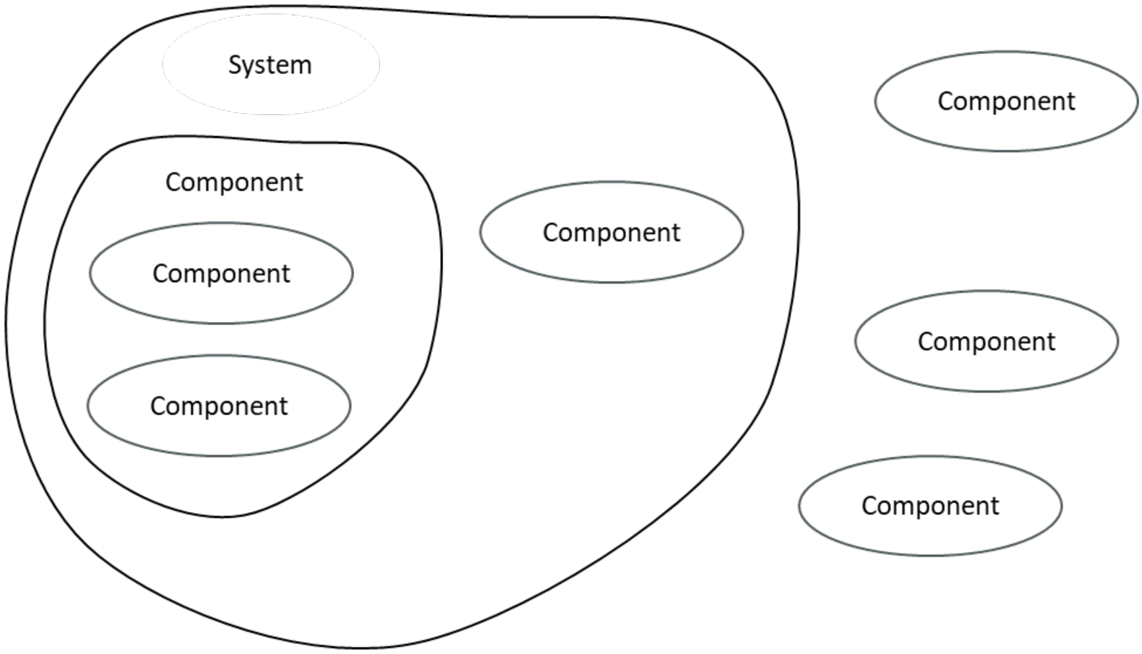


Figure 15: Generalised Systems Map

An example of the technique's application can be seen in work undertaken within the road sector, where the unintended consequences of various decarbonisation policies associated with electric vehicles were investigated (Penn *et al.*, 2022).

9 Performance analysis

9.1 Analysis of systems approaches and methodologies

The following table summarises key characteristics of the systems thinking methodologies and tools discussed here. It highlights their strengths, weaknesses, required expertise levels, applicability to different project stages and transport-related applications. This comprehensive analysis serves as a foundation for understanding their role in addressing systemic challenges and opportunities in transport systems.

Table 4a: Characteristics of systems thinking methodologies

Methodology	Pros	Cons	Level of expertise required	Stage of development	Applications
Backcasting	Promotes long-term planning for sustainability and safety. Focuses on desired outcomes over constraints.	Data-intensive. Relies on accurate predictions of external factors. May overlook short-term challenges.	High	Strategic planning, policy formulation.	Sustainability goals, transport policy frameworks.
Boundary Judgements	Reveals diverse stakeholder perspectives. Encourages critical reflection on inclusivity and boundary critiques.	Requires advanced expertise to identify and evaluate diverse judgements. Potential disagreements over system boundaries.	High	Initial project scoping, boundary definition.	System boundary critique, multi-stakeholder analysis.
Critical Systems Heuristics (CSH)	Facilitates critical reflection on assumptions. Enhances decision-making transparency. Encourages inclusivity	Requires skilled facilitation. Outcomes can be subjective. Time-intensive.	High	Scoping, policy evaluation, boundary critique.	Stakeholder accountability, disaster management.
Critical Systems Thinking (CST)	Integrates diverse methodologies for holistic problem-solving. Promotes inclusivity and stakeholder empowerment. Flexible and adaptable.	Advanced expertise needed for integration. Time-intensive. Complexity may be challenging for newcomers.	High	Strategic interventions, evaluation of complex problems.	Transport policy, systemic risk management.
Delphi Method	Builds expert consensus. Facilitates prioritisation of issues. Incorporates diverse perspectives.	Time-consuming iterative process. Requires skilled moderation. Potential bias from dominant voices.	High	Strategic planning, prioritisation of research needs.	Road safety research, technology feasibility studies.

Methodology	Pros	Cons	Level of expertise required	Stage of development	Applications
Failure Modes and Effects Analysis (FMEA)	Identifies potential system failures. Quantifies risks. Enhances reliability and safety.	Resource-intensive. Requires detailed component analysis. Limited by the quality of input data.	Moderate	Risk assessment, reliability improvement.	High-speed rail, marine safety systems.
Socio-Technical Systems Theory (STS)	Integrates technical and social components. Optimises organisational performance. Enhances adaptability.	Limited to organisational contexts. May not address all system layers. Complexity in application.	High	Design and optimisation phases.	Maritime safety, lean management.
Soft Systems Methodology (SSM)	Encourages stakeholder engagement and shared understanding. Provides a holistic view. Flexible across contexts.	Time-consuming to implement. Requires detailed facilitation. Relies on stakeholder participation.	High	Early project planning, diagnosing systemic issues.	Risk assessment, multimodal governance, policy evaluation.
Stakeholder Analysis	Simplifies stakeholder engagement. Identifies stakeholder roles and relationships. Enhances inclusivity.	May oversimplify complex dynamics. Relies on accurate categorisation. Subjective if poorly executed.	Moderate	Initial project scoping, stakeholder mapping.	Safety frameworks, policy development.
Strategic Options Development and Analysis (SODA)	Facilitates participative decision-making. Supports cognitive and causal mapping. Encourages collaborative solutions.	Relies on stakeholder engagement. Outcomes may depend on facilitation quality. Requires expertise in mapping.	Moderate	Problem diagnosis, decision-making phases.	Accident prevention, transport investment planning.

Methodology	Pros	Cons	Level of expertise required	Stage of development	Applications
SWOT Analysis	Simple and widely understood. Facilitates strategic evaluation. Engages participants effectively.	May oversimplify complex problems. Relies on participant insight. Outcomes can be subjective.	Moderate	Strategic decision-making, scenario analysis.	Aviation strategies, rail and road terminal planning.
System Dynamics	Captures feedback and time delays. Models complex interactions. Provides visualisation of causal relationships.	High learning curve. Requires advanced modelling skills. Time-intensive to construct models.	High	Dynamic modelling, impact analysis.	Urban rail and road systems, safety interventions.
Viable System Model	Provides a framework for diagnosing organisational viability. Supports systemic evaluation. Offers a holistic view of interrelationships.	Limited to organisational design. Requires understanding of model components. May oversimplify broader system issues.	Moderate	Organisational diagnostics, system design.	Transport system evaluations, organisational redesign.

Table 4b: Characteristics of systems thinking communication tools

Communication tool	Pros	Cons	Level of expertise required	Stage of development	Applications
Activity Sequence Diagrams	Easy to construct and interpret. Helps define processes clearly. Widely applicable.	Limited depth for highly complex systems. Relies on accurate sequence information. May oversimplify dynamic systems.	Low	Documenting processes, supporting other systems tools.	Project management, process improvement.
Conceptual Modelling	Supports logical sequencing and problem definition. Enhances understanding of purposeful activities.	Requires understanding of systems perspectives. Can be time-consuming for detailed scenarios.	Moderate	Initial problem scoping, model development.	Used in SSM, VSM applications.
Control Model Diagrams	Highlights regulation processes clearly. Simplifies complex control systems.	May not capture all system dynamics. Limited use in non-regulatory contexts.	Moderate	System regulation design, performance evaluation.	Control system design, organisational regulation.
Influence Diagrams	Visually represents decision-making frameworks. Identifies relationships between decisions and uncertainties.	Requires clarity in relationships. May oversimplify interactions.	Moderate	Decision-making, system failure analysis.	Aviation system failures, maritime weather disruptions.
Multiple Cause Diagrams	Illustrates causes of change effectively. Facilitates understanding of situational dynamics.	May become cluttered with complex systems. Requires careful structuring.	Moderate	Root cause analysis, change management.	System change analysis, causal investigation.

Communication tool	Pros	Cons	Level of expertise required	Stage of development	Applications
Rich Pictures	Provides a visual summary of situations. Captures multiple viewpoints effectively.	Informal; may lack precision. Highly subjective to the creator's perspective.	Moderate	Problem framing, stakeholder engagement.	Intermodal terminal analysis, policy evaluation.
Root Definitions	Defines systems purposefully. Provides structured descriptions for modelling.	Relies on accurate stakeholder inputs. Limited application outside of SSM.	Moderate	Building activity models, scoping purposes.	SSM applications, conceptual modelling.
Spray Diagramming	Simple and quick to construct. Effective for brainstorming.	Lacks depth in relationships. Not suitable for complex scenarios.	Low	Idea generation, preliminary problem exploration.	Mind mapping, conceptual brainstorming.
Systems Maps	Captures system components and their environment clearly. Allows exploration of boundaries.	Requires a defined perspective. May not capture dynamic interactions.	Moderate	Boundary exploration, system documentation.	Electric vehicle decarbonisation policy analysis.

Table 4 demonstrates the diversity and adaptability of systems thinking tools. The analysis reveals key strengths and limitations that influence their application in transport performance analysis, as discussed further in the following sections.

9.2 Analysis of systems techniques

The tools identified each have unique strengths, weaknesses, opportunities and threats when it comes to their application. However, more importantly, they all share several key characteristics when viewed at the level of approach or technique. The following tables (Table 5 and Table 6) outline these broad characteristics.

Table 5: Analysis of systems approaches and methodologies

Strengths	Weaknesses
Support systemic change in complex situations. Facilitate learning across all participants. Provide documentable evidence of the application of various systems thinking concepts. Can be and have been applied in any socio-technical situation (such as transport systems).	Require prior knowledge or experience to implement. Effective application can take significant effort and investment of time. Many of the approaches do not follow a linear implementation of specific tasks so can be difficult to plan using traditional project management approaches.

Opportunities	Threats
Application increases practitioners' knowledge of broader systems thinking concepts. Approaches can be combined with those from other fields, facilitating cross-disciplinary learning.	May not align with existing policy processes within a practitioner's field, resulting in approaches being disregarded. Core systems thinking concepts can challenge previously held traditions of understanding from other disciplines, resulting in resistance from participants and practitioners.

Table 6: Analysis of systems techniques

Strengths	Weaknesses
Require minimal knowledge or experience to implement. Most require no specialist software. Use encourages application of various core systems thinking concepts. Provide documentable evidence of the application of various systems thinking concepts.	Effective application often requires use as part of a systems approach or methodology. Diagramming conventions for many techniques are similar but subtly different from each other, which can generate confusion.

Opportunities	Threats
Many techniques build on each other as well as the broader systems approaches, thus acting as good entry points into developing systems thinking knowledge.	Interpretation of diagrams requires a basic level of understanding of systems tools and concepts, which can create barriers for a non-technical audience.

9.2.1 Apparent gaps in application within the transport sector

As outlined earlier in this section, this investigation surfaced around 91 studies documenting the application of one or more of the various systems tools within one or more transport modes. Figure 16 illustrates this evidenced application. It should be noted that, given the constraints of this investigation, there may be further examples of the application of specific systems tools within transport modes not included in this analysis.

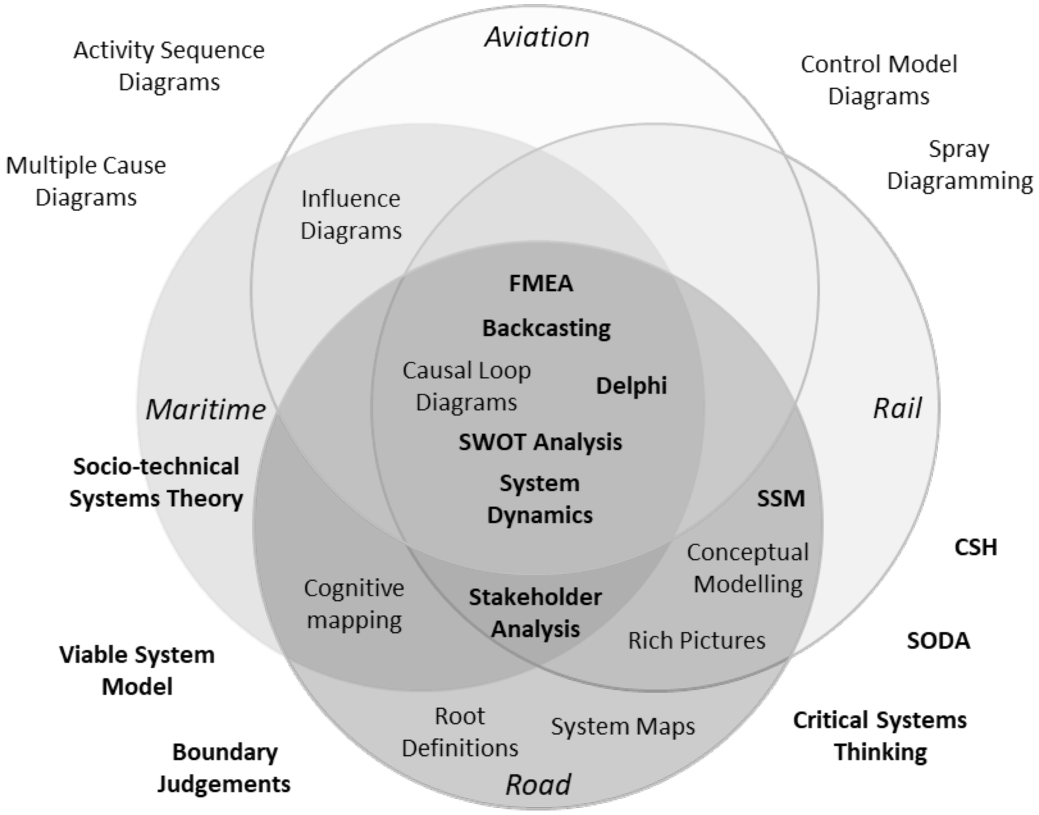


Figure 16: Application of systems approaches (bold) and techniques across transport modes

When analysing the application of tools across transport modes several key points become apparent:

- There was evidence of the application of systems tools across all the major transport modes (aviation, maritime, rail and road).
- There was evidence of many of the systems tools being applied within multiple transport modes (with only three tools appearing to be exclusively applied within single modes: Root Definitions and System Maps used in Road, and Socio-technical Systems Theory used in Maritime).
- The apparent weaknesses of systems approaches and techniques did not limit their application across transport modes (with equal application of the two categories across modes).

- There are several prominent systems tools that appear to have not been applied within the development, operation and use of transport systems (represented by those tools situated outside the diagram in Figure 16): Boundary Judgements, CSH, Critical Systems Thinking, SODA and Viable Systems Model.

Part Three

Summary, conclusions and recommendations

10 Summary: How should we use systems thinking to improve transport safety?

In Part 1 of this document, we used a series of stories to illustrate why thinking about systems and their properties is important for people who are interested in improving transport safety. In Part 2 we presented two sets of systems thinking tools, one of which we described as approaches and methodologies and the other as communication tools. We'll now consider how to decide which, if any, of these tools to use to help resolve a problem we're working on.

Some tools, like the Activity Sequence Diagram, can be applied at different levels to the same problem. Suppose for example that we want to reduce the number of pedestrians struck by vehicles while crossing the road. We can draw an Activity Sequence Diagram to define the steps that pedestrians need to take in order to improve their chance of crossing safely, in a manner that is no doubt familiar (Figure 17).

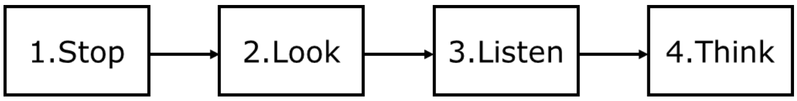


Figure 17: Activity Sequence Diagram for crossing the road

We can also draw an Activity Sequence Diagram for the process to understand the wider reasons for collisions between vehicles and pedestrians and how these might be mitigated and future harm prevented (Figure 18). This broadens the approach to consider all the collision prevention actors in one system.

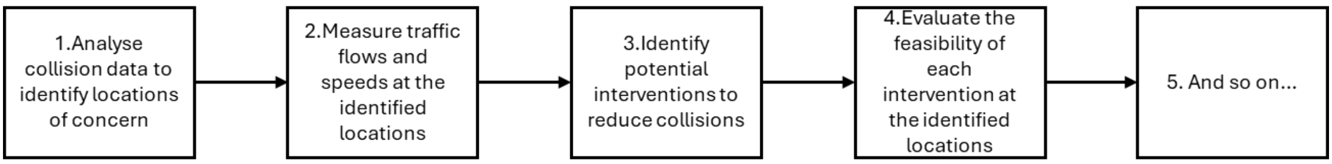


Figure 18: Activity Sequence Diagram for reducing collisions between vehicles and pedestrians

The point is that simple tools, like many of the diagramming techniques described in Part 2 Section 8.3, can be used in a fairly universal fashion, in much the same way that a screwdriver can be used to change a plug or assemble part of a submarine. On the other hand, the more sophisticated approaches and methodologies described in Part 2 Section 8.2 are quite specific in the manner in which they should be applied and the subject matter for which they are useful. For example, Failure Modes and Effects Analysis (FMEA) is only intended to be used to analyse the behaviour of machines (in the broadest sense) and has a very clearly defined process that should be followed in order to reach a valid result. One notable weakness of the FMEA process is that it only seeks to identify "failures", in the sense that something breaks, or at least doesn't work as the designer intended it to. So, if you are interested in, for example, understanding the likelihood and consequences of a failure of the actuator that closes the doors of a lift then FMEA is a highly effective tool. But FMEA is not a good tool for understanding what is often referred to as the safety of the intended function (SOTIF). Consider, for example, the manually operated lift we discussed in Part 1 Section 2 – a user could open the lobby door on the tenth floor and plunge into the lift shaft. In this case there has been no failure of the machine; it behaved exactly as it had been designed to behave. Clearly, though, there has been a failure in the thought process that led to a design which allowed the lobby door on the tenth floor to be opened without the lift car being present. For cases where those SOTIF considerations are important, analysis techniques such as System-Theoretic Process Analysis (STPA) are far more appropriate. The STPA Handbook provides detailed coverage of this technique.

For complex machines it may be necessary to employ a combination of FMEA and techniques such as STPA. In the case of Flight 447, an FMEA had very likely correctly identified that ice in the pitot tube would cause the airspeed indicator to display an erroneous value – this is a well-known failure mode in aircraft of all kinds. But the FMEA would have been of no help in identifying the chain of events that ultimately led to the loss of the aircraft. Apart from the original icing of the pitot tube, for which mitigation measures had already been implemented, there was no failure of any component or system – they all behaved as they had been designed to. The failure in that case was that the designers had not predicted the possibility that a pilot might react in a certain way to an unexpected event, and that the lack of a mechanical connection between the joysticks of the two pilots would make it more difficult for the other pilot to understand what was causing the aircraft to behave in the way it did.

Analyses of this nature will become increasingly important as vehicles become more automated. It is highly likely that automated vehicles will suffer from failure modes in which the machinery behaves exactly as it was intended to, but the outcome is undesirable or dangerous. See, for example, the 2023 crash of a Cruise “robotaxi” in San Francisco in which the automated vehicle, having struck a pedestrian who had been thrown into its path by another vehicle, then made a “minimum risk manoeuvre” in which it pulled over to the side of the road, dragging the pedestrian with it. In this case, the automated vehicle did not cause the initial collision, and it behaved as it had been designed to, but it still exacerbated the injury to the pedestrian because the scenario in which a pedestrian might become lodged under the vehicle had not been foreseen by its designers. It is foreseeable that failure modes – such as users inadvertently being delivered to Newport Gwent when they intended to travel to Newport Shropshire – will become a common occurrence.

Policymakers often find themselves in a position where there is no single correct answer to a particular problem. Indeed, often problems only exist as matters of perspective. Take, for example, the growth of micromobility. From the perspective of the new companies that have been set up to serve the demand for new machines and services, the growth of micromobility is an unquestionable good. But from the perspective of pedestrians, micromobility might be a benefit (if they decide to use an e-scooter instead of walk), might be a problem (if they fall over an e-scooter left lying on the pavement) or could even be both (if they crash into another e-scooter user while riding their own).

Techniques such as the Soft Systems Methodology seek to support the analysis of these complex situations by encouraging the analyst to identify stakeholders within the system and frame the situation from each of their viewpoints. Analysts are encouraged to think of problems not as fundamental entities but rather as subjective phenomena belonging to "problem owners". The Soft Systems Methodology also encourages the analyst to think of problems as messy, complex phenomena rather than simple, discrete issues, as a reductionist thinker might. A reductionist thinker might say the problem is e-scooters get left on the pavement, so the solution is to ban e-scooters. This approach would certainly solve the problem, if we viewed the situation only from the perspective of the pedestrian who tripped over and never rode an e-scooter. We could equally take the reductionist view that the solution is to ban pedestrians – both solutions would have the same effect.

Using the Soft Systems Methodology, the analyst might see it differently:

- The pedestrian owns the problem that they trip over an e-scooter left on the pavement.
- The e-scooter user owns the problem that they don't have an appropriate place to park the e-scooter when they have finished using it.
- The council owns the problem that they don't have the resources to provide a dedicated parking place for e-scooters.
- The e-scooter rental company owns the problem that they are reliant on the council to provide them with appropriate infrastructure for their e-scooters to operate on and are powerless to prevent e-scooters from being discarded on the pavement.

Like problems, the Soft Systems Methodology views solutions as subjective constructs. For example, providing a dedicated parking place for e-scooters might be viewed as the solution to e-scooters being a hazard on the pavement. But this fails to consider the perspective of the user, who might want to travel to a location that doesn't have a dedicated parking space. It also fails to consider the possibility that the original problem was not the result of careless users simply discarding e-scooters at the end of their journey, but was actually the result of third parties vandalising e-scooters that had been parked responsibly. If the latter is true, the actual solution to the problem might be more visible policing to catch the vandals, or integrated locking mechanisms to permit parked e-scooters to be locked to some suitable structure and thus prevent them being thrown to the ground.

The fourth facet of Soft Systems Methodology is that no decisions should be made until the situation has been analysed in detail. This should help to prevent the type of knee-jerk interventions that might result from taking a reductionist, single-viewer perspective on situations.

The limitation of this approach, when applied to questions of safety, is that deaths and injuries due to the use of vehicles is not a subjective problem. As a society we view accidental death and injury as an objectively bad thing. But that is not to say that the Soft Systems Methodology is not a useful tool in helping to understand and solve safety issues. Indeed, the Soft Systems Methodology and similar techniques such as Critical Systems

Thinking (CST) can be helpful in suggesting novel solutions that may not have been considered had a more reductionist approach been used.

Engaging with stakeholders is a key element of systems thinking. Seeking the, often opposing, views of different stakeholder groups can often in itself provide useful insights, which may lead to unexpected solutions. There are a variety of formal techniques for engaging with stakeholders, which usually start with a mapping exercise to identify who those stakeholder groups might be, followed by a questionnaire, interviews, workshops or focus groups. Whatever technique is used, it is crucial to ensure that a broad cross-section of stakeholders are included and that the questioning techniques used are sufficiently open to ensure that alternative perspectives are accommodated and valuable insights are captured. Those conducting stakeholder engagement activities should not be afraid to challenge the views expressed by stakeholders, since sometimes those views might be based on incorrect assumptions or be mediated by external influences.

In Part 2 Section 8.2.7 we discussed the Delphi Method. This is a formalised stakeholder engagement process in which successive rounds of questionnaires and debate are used to develop a consensus position on a certain topic. The Delphi Method is especially popular in medical research, where it is often used to develop guidance on topics that don't lend themselves to more traditional scientific methods such as randomised controlled trials (e.g., the most effective way to extricate an injured person from a crashed car, demonstrated in the EXIT Project). In some senses the Delphi Method is at odds with other systems thinking techniques like the Soft Systems Methodology because it assumes that there are objective problems that can be solved with a single-objective best solution. However, the Delphi Method is a powerful tool for collecting and distilling the insights of a broad cross-section of knowledgeable stakeholders and as such can be extremely useful when seeking to make progress on seemingly intractable problems. A key element of the Delphi Method is that the first stage is extremely open, seeking to draw in a diverse range of opinions and viewpoints before distilling that diverse body of information through the later stages of the process. However, the result of that openness is that the Delphi process can be quite labour-intensive to run and requires a significant amount of time to read and categorise all the responses to the initial questionnaire.

11 Conclusions

- Safety across the transport sector is fragmented in its approach.
- Transport systems are complex, which makes changing aspects of them challenging.
- Systems thinking is a field of practice that aims to help deal with complex situations in order to bring about change.
- A range of theories, concepts, approaches, methodologies and techniques have emerged over time to support those who practise systems thinking.
- Adopting a common description of these tools may help shift the focus of practitioners within the transport sector away from individual tools towards the broader theories and concepts of systems thinking, with an emphasis on improving safety and overall system performance.
- We have mapped the use of 22 of the most prominent of these tools to enhance safety and system performance across the transport sector.
- Our analysis shows that these tools have been used across all the major transport modes (aviation, maritime, rail and road), and many appear to have been applied across multiple modes.
- Regardless of the tool in question, effective application requires a level of knowledge and experience that allows practitioners to contextualise the tools' use to the characteristics of the situation (Ison, 2010).
- It would therefore be beneficial to build the knowledge and experience of systems thinking of those responsible for the safe development, operation and use of all transport systems. This could be achieved by first applying systems tools with lower entry thresholds, so building practitioners' knowledge in order to move onto more complex ones.

12 Recommendations

The key take-away of our investigation is that systems thinking has far more to do with mindset when approaching a problem than the tools that can be used when solving it.

It is important for practitioners to understand that, just because we have drawn an Activity Sequence Diagram or conducted a Delphi study, this does not mean we are suddenly doing systems thinking. The discipline of systems thinking requires an approach to situations that takes into account the broader cultural, technical, economic and environmental influences as appropriate, even if the techniques we use to capture and process those insights are of our own devising and have no formal name. This does not mean that everything has to be quantified, and all interdependencies qualified, before actions or safety interventions or recommendations can be made. Instead, it means consideration must be given to defining and including the important relationships. Systems thinking must never be a barrier or an impediment to safety improvements. The motivation to use systems thinking is to accelerate cost-effective delivery and maximise the safety benefits as quickly as practicable.

In some situations, problems and solutions may be subjective constructs that rely on the perspective of the viewer for their properties. Whether or not we think this assertion is true, by developing a holistic view of any situation and using the insights that the broader perspective gives to understand the positions of the actors in the situation, and using the pertinent insights, we are best placed to propose actions to improve safety and mitigate unintended consequences.

This means that systems thinking is the journey and not the destination. For example, using new insights on how people behave when using technologies (new or old ones), and in given situations, will improve the design and effectiveness of safety interventions. Also, consideration of the range of behavioural responses is a discipline that will become increasingly important as we strive for more healthy and safer journeys. The aim is for no one to be injured or killed when travelling by any mode. Whether or not this is an achievable target, systems thinking provides a practical mindset from which to approach the solutions.

Finally, Figure 16 in Part 2 Section 9.2.1 highlights that different analytical tools are used by different transport modes, which suggests that this is at least in part due to the silo nature of the professional environments across transport, and of course because some tools are more suited to some modes. We recommend more focus on what works for transport safety and, where appropriate, shared learning and application of successes. This could take the form of a national forum designed to disseminate and educate safety professionals in the public and private sectors.

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Systems thinking in transport safety

Cross Modal Safety Change Programme

This report documents TRL's investigation into the adoption and application of systems thinking tools within the transport discipline. It covers a review of available literature, an assessment of 22 prominent systems tools, an assessment of their performance and their suitability for application with regards to making change within the transport sector. In doing so this investigation seeks to provide helpful insights to those who develop, operate and use transport systems as they endeavour to develop more integrated networks and reduce the levels of safety risk experienced by all parties.

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