Integrating complex systems science into road safety research and practice, part 1: review of formative concepts

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ABSTRACT

Many of our most persistent public health problems are complex problems. They arise from a web of factors that interact and change over time and may exhibit resistance to intervention efforts. The domain of systems science provides several tools to help injury prevention researchers and practitioners examine deep, complex and persistent problems and identify opportunities to intervene. Using the increase in pedestrian death rates as an example, we provide (1) an accessible overview of how complex systems science approaches can augment established injury prevention frameworks and (2) a straightforward example of how specific systems science tools can deepen understanding, with a goal of ultimately informing action.

INTRODUCTION

This first paper in a two-paper series addresses opportunities to use complex systems science tools in road traffic injury prevention research and practice. This two-part series aims to (1) discuss how a systems thinking approach can provide new insights in the field of road traffic injury prevention and (2) provide an example of how specific systems science tools can deepen understanding of a persistent injury problem, namely, pedestrian deaths, in the USA.

In this first paper, we review common population health frameworks used to guide road traffic injury prevention research and practice. We discuss road traffic injury as a complex problem, with a specific focus on pedestrian injury. Finally, we introduce a systems science approach and associated tools that leverage core public health and injury prevention frameworks, while overcoming some important shortcomings. Specifically, in response to the perceived need to better integrate systems methods in injury prevention research and practice,[1–9] we provide both an accessible overview of how systems science approaches can augment, and overcome some important limitations of, established injury prevention frameworks and examples of common systems science tools that can be readily applied to persistent road traffic injury problems.

As background to our motivating example, we describe the increasing rate of pedestrian deaths in the USA. Between 2007 and 2017, road traffic–related death rates in the USA decreased by approximately 15%. This decline was evident in both per capita rates (from 13.7 to 11.4 per 100 000 population) and in rates per vehicle mile travelled (from 1.36 to 1.16 per 100 million miles).[10–12] On the face of it, this decline represents an uncomplicated (and very welcome) trend in road safety. However, subanalysis of trends by type of road user reveals a heterogeneous and more complicated story. While large reductions in per capita driver and passenger death rates occurred over this time, with decreases in the range of 25% to 35%, rates among vulnerable road users have remained largely stable or in some cases even increased (figure 1). Specifically, pedal cyclist death rates remained relatively flat, motorcyclist rates decreased by only 8% and pedestrian rates experienced an 18% increase (figure 1B). This paper demonstrates how the use of complex systems tools can deepen our understanding of this troubling increase in pedestrian deaths. We begin by reviewing common population health frameworks and application to road safety.

COMMON PREVENTION FRAMEWORKS

There are several established frameworks that have, thus far, served to guide how the field responds to changing road traffic and other injury death rates. These frameworks include, but are not limited to, the (1) general public health approach, (2) Haddon matrix, (3) social–ecological model and (4) Safe Systems approach. While additional frameworks exist to guide injury prevention research and practice, these four are among the most commonly used in road traffic injury prevention. We briefly summarise them below and demonstrate how they have been applied to the persistent problem of pedestrian injury.

The 'public health approach' has long served as a central framework for addressing population health problems, including road traffic injury (figure 2A).[13] The approach involves four key steps: (1) define the problem, (2) identify risk and protective factors, (3) develop and test prevention strategies, and (4) assure widespread adoption. Accomplishing these steps is facilitated by analysis of data from robust surveillance systems, research on contributing factors and causal mechanisms, implementation and rigorous evaluation of injury prevention programmes and policies, and pervasive adoption, implementation, and maintenance of programmes and policies found to be effective. The public health approach is an iterative process that requires researchers and practitioners to revisit steps as new data and research emerge and as new

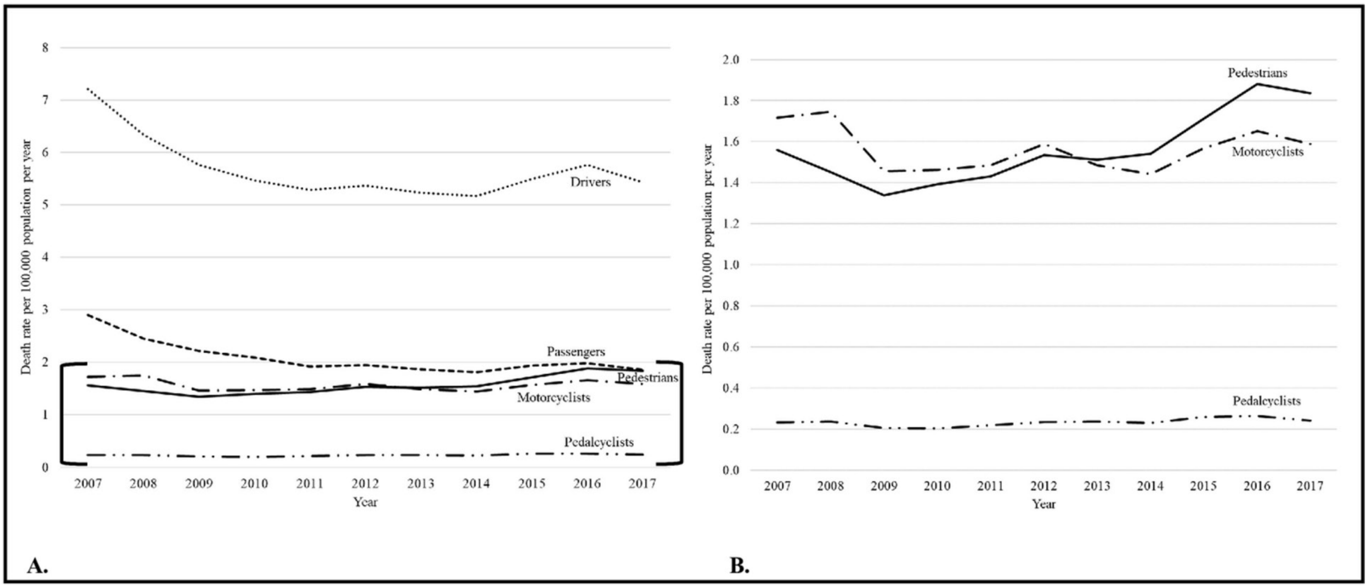
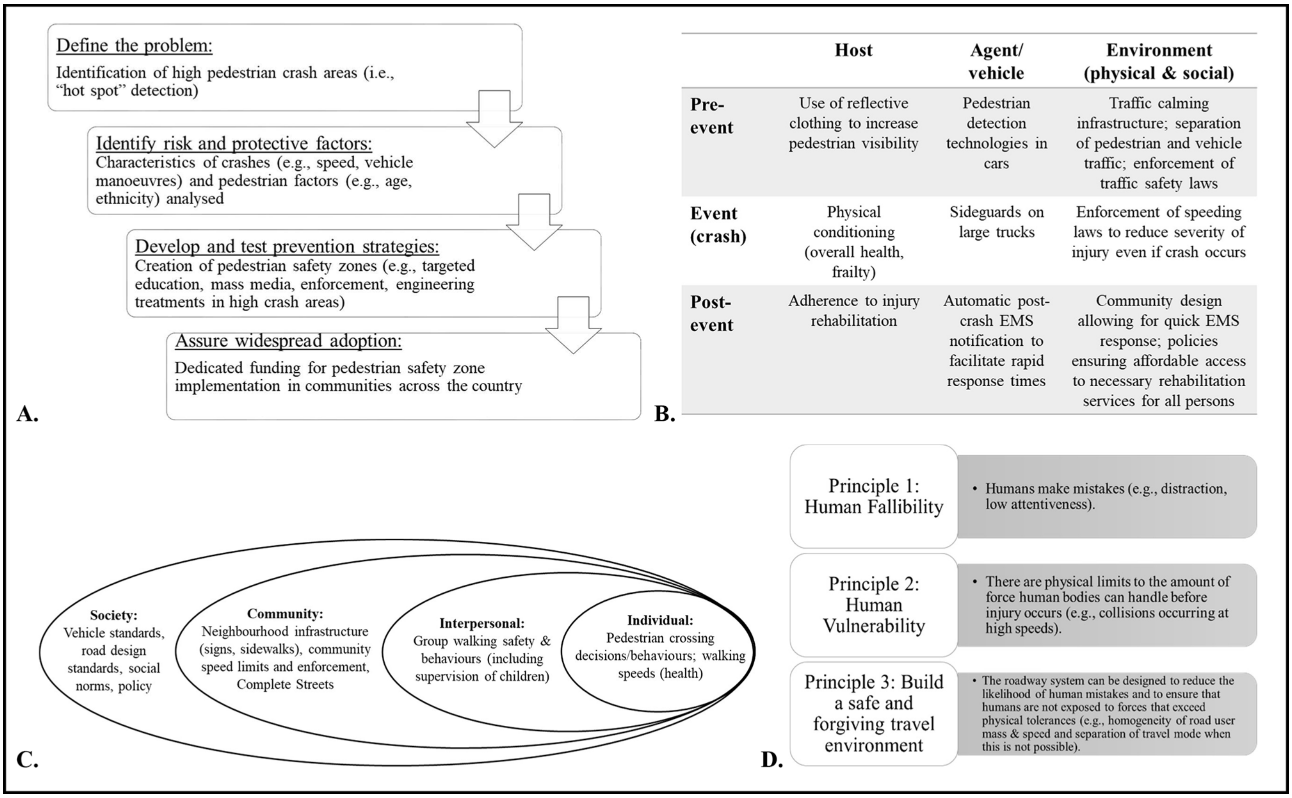


Figure 1 Death rates of all road users per 100 000 population per year (A) and with focus on vulnerable road users (B) by mode, Fatality Analysis Reporting System, USA, 2007–2017. Brackets in (A) highlight the area displayed in (B).

programmes and policies are developed. Figure 2A provides an example of the public health approach applied to pedestrian injury.

The Haddon matrix, originally proposed to inform road traffic–related injury prevention, is well established throughout the broader field of injury prevention.[14 15] The Haddon matrix uses traditional disease prevention concepts of host, agent and environment, and combines them with opportunities for intervention—primary, secondary and tertiary prevention targets—to help understand the problem and develop strategic countermeasures (figure 2B). The three factors, represented by columns, involve the person (host), energy exchange (agent), and physical and social setting (environment) that are involved in the injury process. The three rows in the matrix represent phases of the injury process: pre-event, event and post-event. The matrix is useful for both structured and spontaneous identification of underlying factors involved in the injury process, as well as specific strategies that could be used to intervene at different



Define the problem:
Identification of high pedestrian crash areas (i.e., “hot spot” detection)

Identify risk and protective factors:
Characteristics of crashes (e.g., speed, vehicle manoeuvres) and pedestrian factors (e.g., age, ethnicity) analysed

Develop and test prevention strategies:
Creation of pedestrian safety zones (e.g., targeted education, mass media, enforcement, engineering treatments in high crash areas)

Assure widespread adoption:
Dedicated funding for pedestrian safety zone implementation in communities across the country

	Host	Agent/ vehicle	Environment (physical & social)
Pre-event	Use of reflective clothing to increase pedestrian visibility	Pedestrian detection technologies in cars	Traffic calming infrastructure; separation of pedestrian and vehicle traffic; enforcement of traffic safety laws
Event (crash)	Physical conditioning (overall health, frailty)	Sideguards on large trucks	Enforcement of speeding laws to reduce severity of injury even if crash occurs
Post-event	Adherence to injury rehabilitation	Automatic post-crash EMS notification to facilitate rapid response times	Community design allowing for quick EMS response; policies ensuring affordable access to necessary rehabilitation services for all persons

Society: Vehicle standards, road design standards, social norms, policy

Community: Neighbourhood infrastructure (signs, sidewalks), community speed limits and enforcement, Complete Streets

Interpersonal: Group walking safety & behaviours (including supervision of children)

Individual: Pedestrian crossing decisions/behaviours; walking speeds (health)

Principle 1: Human Fallibility
- Humans make mistakes (e.g., distraction, low attentiveness).

Principle 2: Human Vulnerability
- There are physical limits to the amount of force human bodies can handle before injury occurs (e.g., collisions occurring at high speeds).

Principle 3: Build a safe and forgiving travel environment
- The roadway system can be designed to reduce the likelihood of human mistakes and to ensure that humans are not exposed to forces that exceed physical tolerances (e.g., homogeneity of road user mass & speed and separation of travel mode when this is not possible).

Figure 2 Foundational approaches and frameworks to road traffic injury prevention research and practice: public health approach (A), Haddon matrix (B), social–ecological model (C) and Safe Systems approach (D), populated with pedestrian injury examples.

points in that process. The matrix was expanded to include a third dimension to aid decision-makers in prioritising interventions to implement when faced with many candidate options and limited resources.[16] This dimension helps organise and summarise effectiveness, cost, freedom, equity, stigmatisation, preferences, feasibility and other stakeholder-identified criteria associated with each intervention. The Haddon countermeasures provide a complementary paradigm focused around hazard containment and causal processes.[15]

A third tool used to aid visualisation, understanding and strategic action related to injury prevention is the social–ecological model (figure 2C). This model depicts the interplay between individual, interpersonal, community and societal levels, recognising that each of these layers influence public health problems and that countermeasures are strongest when they target multiple layers.[17] While generally used in violence prevention research and practice, applications to road traffic injury prevention also exist, although are far less common.[18–20] Similar to the Haddon matrix, the social–ecological model helps the user broaden their view of the problem, the interacting layers or components involved in the problem, and with that, the potential opportunities for intervention. This model can also help illuminate the fact that public health problems do not occur in isolation, but rather arise from complex layers of factors.

Fourth, Safe Systems, a more recent approach adopted in the 1990s in countries such as New Zealand, the Netherlands, Sweden and Australia, is a strategy that has been specifically and increasingly applied to the problem of road traffic injury (figure 2D). Similar terminology, such as 'Systemic Safety' and 'Sustainable Safety', have also been used. These approaches sometimes, but not always, are used to support the implementation of a Vision Zero programme. Underlying all of these initiatives is a common premise—serious injuries and deaths should not be accepted as an unavoidable byproduct of mobility.[21 22] The fundamental principles guiding this approach are that (1) people make mistakes and these mistakes can lead to road traffic crashes, (2) the human body has only so much physical tolerance to crash forces before harm occurs, and (3) the design of road systems should help road users employ safe behaviours but also mitigate the consequences of human error. In a Safe Systems approach, the system designers and road users share responsibility for road safety. Tools, best practices and example applications of adopting a Safe Systems strategy are available.[23–25]

Each of the frameworks discussed above play complementary and important roles in our perspective and approach to road traffic injury prevention. Common to, and underlying each, is a data-informed foundation involving consideration of specific risk factors, as well as the multifactorial and multilayered nature of these problems. Another commonality across all four frameworks is the need to recognise the cross-sectoral and multidisciplinary nature of injury prevention work. However, even with approaches informed by rich data and holistic perspectives, public health interventions often do not operate as projected during small-scale or large-scale implementation. We sometimes observe delayed, diluted or deleterious effects that run contrary to expectations. For example, vehicles designed to improve occupant safety can increase risk to subgroups of occupants or increase pedestrian risk,[26] advanced safety features on cars (eg, antilock brakes) can increase risky driving behaviours,[27] and attempts to encourage safer behaviours (eg, designated driver use) can lead to other harmful outcomes (eg, increased excessive drinking among persons relying on a designated driver).[28] One likely reason for these outcomes is that many public health and road traffic injury–related problems are complex systems problems.

ROAD TRAFFIC INJURY AS A COMPLEX SYSTEMS PROBLEM

Complex problems arise from a web of factors that interact and change over time, rendering cause-and-effect hard to intuit.[29–31] Our frameworks (in particular the social–ecological model) help with the conceptualisation of many individual factors and illuminate the considerable detail (or the multitude of factors across many layers) involved. However, a core tenet in understanding and detecting solutions to complex (and often persistent) problems is that we must also acknowledge and account for the complexity caused by interactions between these factors over time.[29–31] These interactions often (1) exhibit non-linearities (eg, threshold effects), (2) are characterised by feedback loops, (3) include time delays, (4) occur among heterogeneous entities and (5) are characterised by adaptiveness.[29–31] Together, these fundamental attributes of complexity can result in policy resistance, rendering a policy's intended effects null or in some cases, unintentionally worsening the problem, as exemplified above.

The *non-linearities* observed in a system refer to the fact that output is often not proportional to any linear combination of inputs.[30 31] The complex problem of pedestrian injury is characterised by many non-linear relationships. For example, research suggests that the relationship between pedestrian exposure (walking) and injury is not linear. A 'safety in numbers' or 'tipping point' phenomenon has been observed, such that pedestrian travel may become safer after a certain level of pedestrian activity is reached.[32] As another illustration, research suggests that the distribution of speeds travelled may contribute to non-linear impacts on pedestrian death. At pre-crash speeds of less than 10 mph, fewer than 5% of crashes result in death; however, fatality risk rapidly increases at higher speeds such that at speeds of 20, 30 and 40 mph, risk increases to 7%, 20% and 50%, respectively.[33] Therefore, relatively small changes in roadway design that increase vehicle speeds by a relatively modest amount can contribute to major increases in the risk pedestrian of death.

Second, *feedback loops* accompany the non-linearities we observe in a system. Feedback loops are closed chains of causal connections that are broadly characterised as either reinforcing or balancing.[29–31] *Balancing loops* work to bring systems into equilibrium or towards a goal (which may or may not be desirable), while reinforcing loops are characterised by exponential growth or decay. In a balancing feedback loop, we observe that a change in a specific factor sets off a causal chain that ultimately counteracts that initial change (resilience), all else held equal. As a simple example (figure 3), consider that as driving trips increase in a certain area, congestion on roadways increases and speed decreases in that area, which in turn reduces the risk of pedestrian deaths. Fewer pedestrian deaths lead to fewer fears about the risk of walking in that area, thereby causing more people to walk, and fewer driving trips. Therefore, through this simplified loop, it is possible that an increase in driving trips in a given area could eventually loop back around to cause a decrease until the balance is restored at equilibrium.

On the other hand, in a *reinforcing loop*, an increase in one factor ultimately loops back around to cause a further increase in that factor, all else held equal. For example, an increase in driving trips also causes increases in fuel use, which could in turn cause increased fuel tax income for state and local governments. With increased income, governments could fund car-centric infrastructure improvements (eg, road widening), which could then further increase driving trips. In this example, the increase

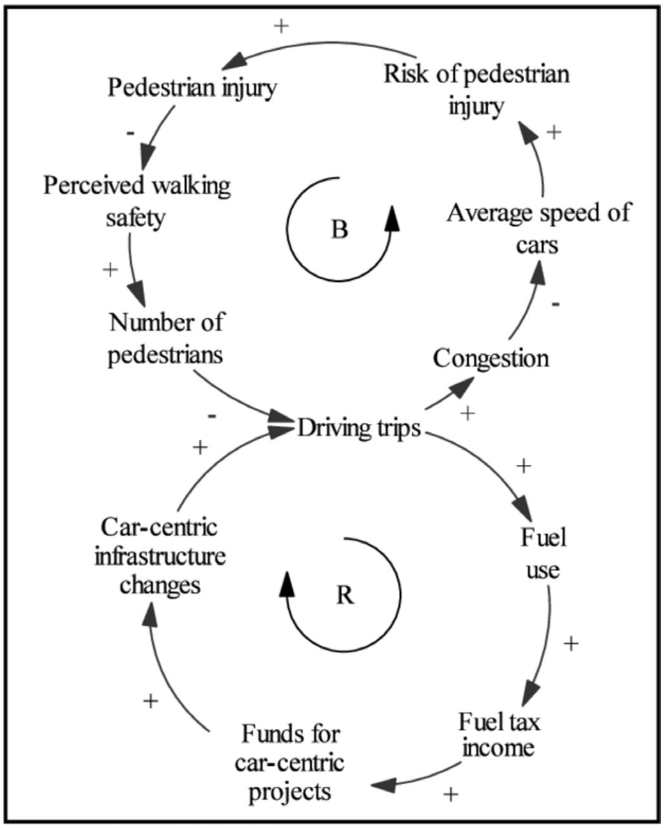


Figure 3 Example causal loop diagram demonstrating hypothesised balancing (B) and reinforcing (R) feedback loops. Arrows represent hypothesised causal relationships; '+' is translated as a change in the factor that an arrow is originating from causes a change in the factor that the arrow is pointing to in the same direction, all else held equal; '–' is translated as a change in the factor that an arrow is originating from causes a change in the factor that the arrow is pointing to in the opposite direction, all else held equal.

in driving trips induces a chain of effects that ultimately causes a further increase in driving trips (figure 3). Shifts between the types of feedback loops that are most active or dominant in a system (ie, specific reinforcing vs balancing loops) at a given time point can help explain changes in an observed outcome (eg, pedestrian injury and death) over time.

Third, *delays* in the speed at which inputs trigger change is critical to understanding the complexity of systems.[30 31] Changes in social norms, attitudes and policy are often delayed with respect to their triggers. This can make linking causes to effects especially challenging, particularly when one does not have a full view of the underlying system. For example, while a pedestrian death might trigger interest in funding more pedestrian-friendly infrastructure, these projects take time to design, approve and build, such that impacts on pedestrian safety will not be immediate. The urgency for action may also dampen before changes are implemented. Delays and their interactions with other processes occurring on different time scales can challenge our intuitive understanding of cause and effect and our ability to predict system behaviours across extended time horizons.

Fourth, *heterogeneity*—or variation for example in individuals or circumstances around an injury event, the broader community/state/national context and/or the organisations (potentially) intervening—can impede understanding of problem causes and optimal solutions.[34] Understanding these details, and interactions among heterogeneous entities that produce outcomes, is critical to preventing injury in diverse settings. We know, for example, there is tremendous heterogeneity in the characteristics of individuals involved in and the circumstances under which pedestrian injuries and fatalities occur. Meaningful variation is observed across age and sex (both driver and pedestrian), alcohol/substance use, pedestrian manoeuvres (ie, crossing at/not at a crosswalk, playing or standing on a road, darting into traffic, walking with traffic, working on road/vehicle), lighting, weather and temporal factors[35] Understanding the interactions between heterogeneous components allows us to better understand the emergent behaviours and problems that result.

Finally, the problem of road traffic injury is *adaptive*.[30 31] Threats to and efforts to support road safety are ever changing due to ongoing developments in technology and the shifts in human driving culture, among a variety of other changes. With the proliferation of technology, there are continually new sources of distraction that increase road traffic injury risk for both pedestrians and drivers. Additionally, research suggests that driving behaviours adapt to new car safety technologies with increases in risk-taking behaviours linked to an increased reliance on vehicle technologies and an assumption that the car will 'step in'.[36] The adaptive, learning and changing nature of a system can often contribute to the persistent nature of problematic outcomes. Some of this adaptation is '*exogenous*' (external)—for example, evolving cell phone capabilities driving distraction—to a system we may be examining. Other elements are '*endogenous*'—driven by the feedback loops in the system—such as market demand and push for increased car safety features in response to real or perceived increases in crash risk. An understanding of these attributes of complexity illuminates some of the limitations of current approaches to fully address the problem of road safety. Traditional approaches provide essential tools for exploring the multifactorial and multilayered nature of road traffic injury problems (figure 2) and aid in identifying the considerable detail involved. However, traditional frameworks inherently lack the ability to elucidate complex (eg, manifold and interconnected, non-linear or time delayed) and adaptive interactions over time. Furthermore, we often rely on reductionist methods and models to examine relationships between a subset of the hypothesised risk factors and outcomes and to ultimately inform intervention choices. While these tools (eg, generalised linear models used to isolate an exposure–outcome relationship) provide a necessary piece of the solution, they do not provide a means to hypothesise about, test and analyse the underlying dynamics of the larger system of interacting factors over time. Nor do they provide a firm basis for deepening our understanding of the inherent complexity of the road safety problem. Effective intervention on injury problems requires a toolbox of approaches and methods that foster our ability to more deeply understand the pieces of the problem, while not losing sight of the complexity and context within which those pieces interact and reside.

INTEGRATION OF A COMPLEX SYSTEMS SCIENCE APPROACH IN ROAD TRAFFIC INJURY PREVENTION

The umbrella of systems science covers many tools that are critical for helping researchers and practitioners *examine complex and persistent problems as systems*, to understand when, with whom and how best to intervene, and to know how to align action capable of improving outcomes. Depending on the research and/or practice goal, tools include both qualitative and quantitative methods to study 'wholes', or systems shaping a given problem or outcome.[30 34] For example, qualitative methods include hypothesising about potentially impactful factors using a detailed systemic analysis framework (eg, AcciMap,[37 38] telling 'dynamic stories' about cause and effect through annotation of graphs over time, drawing causal loop diagrams, or process flow diagramming), while quantitative methods include system dynamics simulation modelling, agent-based modelling, discrete event simulation and social network analysis, among others. Generally, multiple tools are employed throughout the course of a systems-oriented project and both qualitative and quantitative tools are used to complement and inform one another.[39 40] Notably, Salmon and Read demonstrate the complementary insights that can be derived from using multitool or multimodel approaches when seeking to understand and intervene on complex problems.[40] While not exhaustive, we discuss a few examples of qualitative and quantitative tools below that hold promise for transforming the way we study and intervene on road traffic injury problems. Practitioners often talk about poor outcomes stemming from 'broken systems'. We argue that systems are not broken; they are delivering the outcomes consistent with their design. Unless researchers and practitioners understand complex systems, more holistically, we are unlikely to design and implement solutions that will deliver desired change.

Qualitative systems science tools can serve several purposes: to generate robust hypotheses about the complex interconnections and dynamics determining a trend(s) or challenge assumptions, to organise and present a range of perspectives, to illuminate knowledge and data gaps, and to strengthen communication and dialogue among key stakeholders. One example involves use of a broad *hypothesis-generating framework*, *AcciMap*, which can be used with diverse stakeholders to identify potentially impactful interactions between key sociotechnical levels (eg, government/regulatory bodies, technical/operational management, physical processes, actor activities, equipment and surroundings), including vertical flow of decision influence and information.[37 38] This approach guides hypothesis generation amidst complexity, creating a visual depiction of interactions found to support enhanced cross-system communication.[38]

Another example, *graphs over time (GoT) elicitation*, provides a means of visualising and hypothesising about trends and dynamic relationships between trends over time.[41] GoT differ from traditional trend line examination in that they are generally used as a tool to plot changes in both variables for which we do and do not have data. Thus, GoT provide a means for considering and hypothesising about the dynamic interconnectedness of numerous factors over time. GoTs are often annotated, discussed, and reworked in a way that allows stakeholders to view a problem from multiple angles and present hypotheses about key interactions driving a problem. Furthermore, plots are often extended to future time points as a way to develop shared goals among stakeholders and visualise hypotheses about what might happen under various scenarios of action or inaction. In the context of pedestrian safety, pertinent GoTs might depict changes in vehicle miles travelled, pedestrian death rates, economic indicators, vehicle fleet characteristics, poverty and homelessness, and substance use over time to serve as a tool for discussing key potential interactions driving the problem.

Causal loop diagrams (CLDs) are often coupled with GoTs to begin to uncover the structure of dynamic interactions that may be driving a problem.[30] CLDs are diagrams that illustrate hypotheses about the causal mechanisms at play in a system. The causal mechanisms are illustrated using arrows from cause to triggered effects (figure 3). A key component of these diagrams is the explicit display of hypothesised feedback mechanisms, or places in a system where the outcome of a causal process feeds back to the source or input of that process to continuously drive change. Displaying and communicating about these underlying causal structures and feedbacks is critical, as loops and delayed downstream effects often underlie unintended consequences or attenuated effects of prevention efforts. Frameworks, like the Haddon matrix and social–ecological model, can provide useful starting points for constructing CLDs, through their use as tools to elucidate potential factors involved in injury processes. By deepening understanding of the multiple layers of factors likely involved (as elucidated via one or more of the four traditional frameworks discussed above), researchers and practitioners can then use CLDs to work through the potential feedbacks, time effects and other key dynamics at play.

As AcciMap, and other qualitative systems frameworks,[40] is meant to spur stakeholder discussion, *system dynamics group model building* (GMB) can provide an effective platform for developing systems thinking capacity among stakeholders and involving them in the development of systems diagrams, like CLDs, and models around a problem.[42] GMB provides an environment to foster communication, uptake and buy-in for interventions; increases dialogue among both stakeholders implementing interventions and affected by potential implementation; and seamlessly integrates qualitative and quantitative systems tools that can be useful for informing policy and intervention decisions. In the second paper of this series, we detail a GMB process, involving a range of stakeholders, to explore dynamic hypotheses around pedestrian injury trends and demonstrate use of specific complex systems tools.

Building from qualitative tools like AcciMap, GoTs, CLDs and others either within or outside of the context of GMB, there is often a need to quantitatively test systems theories and rigorously examine the best course of intervention action. *System dynamics simulation models*, *agent-based models*, *discrete-event simulation models* and *social network analyses* are just a few of the systems tools that allow researchers to effectively integrate and work within the complexity to quantitatively explore and test intervention and policy scenarios.[34 43]

System dynamics simulation models provide a quantitative modelling approach, using a series of coupled, non-linear, differential equations, to simulate hypothesised complex and dynamic relationships and to examine the impacts of specific changes to a system (eg, through proposed interventions and policies).[44] They can be highly effective for weighing policy options and testing interventions, exploring potential unintended impacts, and developing a shared vision and approach to a problem.[45–48] A system dynamics simulation model can allow researchers and practitioners to virtually test individual interventions (eg, examining impacts of a pedestrian safety mass media campaign), like in step 3 of the public health approach, or examining effects of systemic infrastructure changes (eg, separation of pedestrians from vehicles), consistent with a Safe Systems approach. Additionally, the parametrisation of such models requires a rich evidence base of specific causal relationships to help inform model components (eg, detailed understanding of impact speeds and risk of pedestrian death). In other words, traditional frameworks and methods provide essential inputs to a systems science approach, and systems science tools can help fill gaps in the collection of traditional road traffic injury prevention methods.

Agent-based models, *discrete event simulation models* and *network models* provide additional tools to acknowledge and incorporate dynamic environments and ultimately gain insight into potential outcomes given specific interventions.[34 43 49–52] Agent-based models involve individual-based microsimulations of rule-based actions and interactions of heterogeneous 'agents'

Table 1 Attributes of a sampling of complex systems science approaches

	System dynamics	Agent-based modelling	Social network analysis	Discrete-event simulation	AcciMap
Prototypical problem motivating its use	Learning and action around persistent or policy-resistant, dynamically complex problems with interconnected stakeholder responses	Learning about the relationship between micro-level rules and macro-level outcomes. Examining mechanisms of emergent outcomes	Describing the nature of connections within a network, identifying the implications of structure on outcomes, identifying key nodes/connections	Estimating the impact of system redesign (eg, system capacity and work processes) on consumer queueing, cost and other performance outcomes	Identifying the cause(s) of an accident by studying the system in terms of the many potential decisions, events and interactions that led to the accident. Contributory factors are grouped across six hierarchical levels
Illustrative example	Comparison of policies designed to increase bicycle commuting in a car-centric city. Compared 'what-if' policy scenarios on several outcomes, including injuries, physical activity, air pollution and fuel costs (Macmillan *et al*[45])	Construction of a virtual transport system to explore the mechanisms underpinning the 'safety in numbers effect', including assumptions related to bicycle density (Thompson *et al*[50])	Description and analysis of a range of road users' situational awareness in challenging traffic environments, such as at intersections. Network structure of situational awareness concepts were compared across road user types (Salmon *et al*[55])	Examination of emergency department operations as it relates to average treatment times and outcomes for patients. Simulated and compared different triage approaches on patient outcomes (Connelly and Bair[53])	Elucidation of decisions and actions of actors who share responsibility for young driver road safety, moving beyond a purely driver-centric view. Contributing factors at the following levels: government policy; regularly bodies and associations; local area government, planning and budgeting; technical and operational management; physical processes and actor activities; and equipment and surroundings were identified, as well as key interactions between them (Scott-Parker *et al*[60])
Theoretical underpinnings	Engineering and management (Control Theory)	Social and behavioural sciences	Sociology	Operations and systems engineering	Risk management
Qualitative, quantitative or mixed approach	Mixed	Quantitative	Mixed	Quantitative	Qualitative
Core components/structures of models	Stocks, flows, feedback loops, delays	Agents, state charts, rules of behaviour and adaptation	Nodes and edges	Arrival, queueing and service processes (rules, capacity, times)	Sociotechnical levels and connections/interactions

(eg, cars, people) within a simulated environment (either stylised or realistic) to learn about the resulting macro-level consequences of micro-rules.

Discrete-event simulation provides another tool for simulating the behaviour and functioning of a system, such as the way a facility operates or the efficiency of an emergency department system.[43,53] Discrete-event simulation modelling involves organising a system as an ordered sequence of events or states and allows for complex rules and logic to be incorporated. These models can help improve stakeholder decision-making and policy-making in the midst of a complex environment with many interactions.

Social network analysis involves the analysis of different nodes (eg, people) and the ties (eg, relationships) between the nodes.[34,43] One could easily envision how examining whether and to what extent pedestrian and driver behaviours and interactions change in response to each other and different policy scenarios, or exploring how specific interventions might alter a network of road traffic injury prevention–related partnerships, would provide significant contributions to prevention efforts. We refer the interested reader to more detailed discussions of these quantitative systems science tools[30,49,54] and to specific applications in the road safety field.[50–53,55–59] In addition, table 1 includes a brief overview of a sampling of different systems approaches with key characteristics and example applications.

CONCLUSION

Established road traffic injury prevention frameworks and traditional methods provide key benefits for detailing the multilayered nature of factors involved in injury problems, examining specific causal relationships, and recognising the need for rich data and multiple perspectives. However, these methods have limitations in terms of understanding and effectively intervening on persistent road traffic injury–related trends. The field of systems science provides several tools that have potential to augment current prevention research and practice, and while few, exemplary applications exist in the road safety literature.[6,9,40,45–48,50–53,55–60] These tools, like CLDs in a GMB context, can advance researchers' dynamic hypothesis generation and can also serve as a platform to strengthen dialogue among stakeholders, discuss underlying injury processes that may not be readily apparent and develop shared buy-in for collaborative actions. In addition, quantitative complex systems modelling approaches allow for intervention and policy testing in a simulated context, providing stakeholders with a way to test dynamic hypotheses, evaluate different strategies, and learn about potential benefits and unintended consequences that may result from an intervention prior to real-world implementation.

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