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Harrison, G orcid.org/0000-0002-4324-772X, Grant-Muller, SM and Hodgson, FC (2021) A review of transport-health system dynamics models. Journal of Transport & Health, 22. 101138. ISSN 2214-1405

https://doi.org/10.1016/j.jth.2021.101138

A Review of Transport-Health System Dynamics Models

Abstract

Introduction

The impacts of transport on health have been extensively studied, yet there has been less focus on the complex interactions that exist within the transport-health sphere. We adopt a System Dynamics (SD) approach to addressing the research question *"Where are the trade-offs and synergies between different types of health impacts within the transport-health system?"*, which is in recognition of the problem that policies designed to influence health outcomes related to one form of transport impact may also influence other health outcomes and transport impacts.

Methods

To begin, we carry out a literature review of existing SD studies of transport-health, identifying 23 that have been published, of which six explicitly cover multiple transport impacts. We then combine key concepts of these studies to create a generalised causal loop diagram (CLD) that addresses the research question.

Results

We develop a CLD for exploring the trade-offs within transport-health. In doing so, we find that not all existing studies define health outcomes (eg morbidity or mortality) and few cover both transport and health mechanisms in detail. As well as improving the detail on mobility behaviours, transport impacts and health outcomes, we also identify a need for this approach to consider the influence of new data and technologies on transport-health.

Conclusions

Although this paper presents a qualitative model, this is the first step towards a quantitative model, and nonetheless, in itself may be used to better understand the system and scenarios, and contribute to more robust transport-health impact assessments for policy making.

Keywords: *transport-health, system dynamics, causal loop diagram, policy trade-offs*

1. Introduction

Although the connections between transport and health may have been recognised for centuries, the complexities of these from a cross-sectoral and multi-disciplinary viewpoint have only been studied since the mid-20th century (Widener and Hatzopoulou, 2016), alongside growing mobility and dominance of personal motorised vehicles. Transport is fundamental to economic and social development (Nieuwenhuijsen et al., 2016), but both direct and indirect health impacts can be relatively large and disproportionally focused on certain sub-populations (eg those with pre-existing conditions, particular areas, often associated with deprivation), though given less consideration than conventional transport impacts in policy strategies (Litman, 2013). In urban areas, 20% of all-cause mortality could be prevented by compliance with international recommendations regarding amount of physical activity, environmental exposure and access to green space related to transport (Mueller et al., 2017). Research into transport-health is diverse and broad (Widener and Hatzopoulou, 2016). Although these studies may focus on details of specific aspects of transport-health (eg pollution, physical activity, safety, security, disease diffusion, mental health and well-being), complex conflicts and trade-offs may exist within the wider transport system (Grant-Muller, 2017). Understanding of these is required to ensure research is correctly contextualised and policies can be positioned within a wider holistic framework.

In our study we propose a System Dynamics (SD) approach to capturing these complexities. This modelling method will allow generalised study of the many connections, trade-offs and synergies in a transport-health system, as well as more detailed study of specific aspects within the system. In this way, policy scenarios may be simulated and assessed in terms of specific impacts while considering all aspects within transport and health equally.

The research objectives of this study are thus two-fold. We first of all review existing studies applying SD to ask what are the similarities and differences between these existing models, as well as identifying where research gaps may exist that aren't addressed. We then seek to combine these to create a generalised Causal Loop Diagram (CLD) that addresses the research question of *"Where are the trade-offs and synergies between different types of health impacts within the transport-health system?".* This is in recognition of the problem that policies designed to influence health outcomes related to one form of transport impact may also influence other health outcomes and transport impacts. We acknowledge that this research question has been heavily addressed in previous literature (see for example (Litman, 2013, Stankov et al., 2020, Khreis et al., 2019)), but will demonstrate not only the contribution that SD could make to this field but also that those existing SD models that attempt to do so may lack some fundamental features for answering our research question. For the purpose of our work we aim to adhere to the WHO definition of health as a *"a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity"* (WHO, 1946), and are interested in identifying measureable health outcomes (ie morbidity or mortality), which may sometimes be seen as exogenous to the system, as well as endogenous risk factors from transport associated with these.

The remainder of this paper is set out as follows. In the following section (2) we present a general background to transport-health modelling and in particular set out the contribution that a SD approach could make. We then (Section 3) describe our methodological approach, which involves a thematic literature review of SD studies of transport-health and constructing a CLD from those findings. Our review is in the next section (4), describing the findings, and then we present our combined CLD in Section 5. We offer a critical reflection on our findings in Section 6 and in the final section (7) are our conclusions to the paper, including considerations of future work.

2. Background

There is no shortage of models of transport systems, employing various methodologies and approaches. They do however tend to each focus on one particular aspect or impact of transport. Although (quantitative) Health Impact Assessments (HIA) are seen as important in decision making, integration into transport planning processes is rare (Nieuwenhuijsen et al., 2020), but increasing (Nieuwenhuijsen et al., 2017), though methods vary widely (Waheed et al., 2018). This said, HIA's have been most commonly used in the transport sector in Europe, followed by housing/urban planning (Blau et al., 2006). Although numerous quantitative transport related HIA models exist (which generally follow comparative risk assessment approach – see for example: (Mueller et al., 2017, Stevenson et al., 2016, Woodcock et al., 2009, Kahlmeier et al., 2017), or further detail in Nieuwenhuijsen et al. (2020)), they generally have only been applied as case-study examples within research projects, rather than for practical policy application.

Nieuwenhuijsen et al. (2017) advocates for "*novel participatory integrated full-chain HIA models, methods and tools"*, as no such model currently exists. Although our approach, SD, is not an HIA as such, it could contribute to their proposed framework. They advocate the merits of both separate and co-existing qualitative and quantitative approaches, which SD already incorporates, and recognise that HIA's face a similar key challenge to SD modelling – namely obtaining high quality (and especially baseline) data. In further support to this, Litman (2013) advocated for better models of travel activity alongside investigation of the impacts on all aspects of public health, Stankov et al. (2020) recognise the potential of systems-based simulation models in identifying effective policy outcomes and Widener and Hatzopoulou (2016) suggest that taking a systems perspective may reveal innovative research agendas.

2.1. Overview of System Dynamic modelling in a transport-health context

Both transport and public health are complex dynamic systems, making System Dynamics (SD) an ideal approach for understanding the feedbacks that exist within them, and consider improvements that can be made within the system. SD is a method of capturing behaviours and understanding change of complex systems over time, combining both qualitative systems thinking (Meadows, 2008) and quantitative dynamic simulation modelling approaches. An SD model is a computer simulation of a system of inter-connected equations (Dekker, 2017), developed from Causal Loop Diagrams (CLDs – 2.2.2) and Stock Flow Models (SFMs – 2.2.3), which captures key variables, feedback loops, stocks & flows and system delays. It can be applied to a range of problems, including business operations, public policy and global issues. For a brief overview of SD see SDS (2020), system concepts in the context of policy making see Sterman (2006), or for more in-depth description we recommend the text book of John Sterman (2000a). In the following sections we will describe some key elements of SD methodology and brief overviews of its use in both transport and health studies.

2.1.1.The Modelling Process

As set out in Figure 1, the modelling process (Sterman, 2000b) begins with identification of a problem followed by the qualitative development of the theory on how the problem arises. The Problem Articulation step establishes the purpose of the model, requiring determination of boundaries, time horizons and key variables, as well as identification of behavioural trends that describe the problem being addressed. Best practise in this area requires engagement with stakeholders/decision-makers, statement of purpose, identification of reference modes and current behaviours (Martinez-Moyano and Richardson, 2013). Within the Dynamic Hypothesis step we seek to develop theories that explain the problematic system behaviours, developing visual representations of these causal structures called Causal Loop Diagrams (CLD) or Stock Flow Models (SFM). Through developing an endogenous explanation of these behaviours, one can begin to consider policy solutions and exogenous influences that may solve the problem. Martinez-Moyano and Richardson (2013) refer to this as System Conceptualisation and for it to be exemplary it should be approached creatively (from multiple angles) and be focused on stakeholders mental models. It is these first two stages that we are concerned with in this study. In our case, the Problem Articulation is defined by our research question, *"Where are the trade-offs and synergies between different types of health impacts within the transport-health system?".* The need to identify and understand cross-sectoral impacts of transport schemes was recognised by (Grant-Muller, 2017) giving us our model purpose (focusing specifically on transport-health), and we build on this by carrying out a literature review of related studies that allows us to position that question in terms of the most important variables, behaviours and possible time horizons. The Dynamic Hypothesis is also achieved through this literature review, via the identification of both endogenous and exogenous variables within the defined boundary of a system and establishing the qualitative relationships and feedbacks that exist between these to create a CLD. In the Formulation step, a system of coupled equations based on the SFM is developed to create a quantified computer simulation of the system and may have a more detailed range of both exogenous and endogenous variables than the CLD or SFM. Testing may begin alongside Formulation, and is concerned with the verification and validation of the model (eg through assessment of model structure or behaviour and calibration against historic data), Once there is confidence in the model, it can then be used to design and evaluate policies.

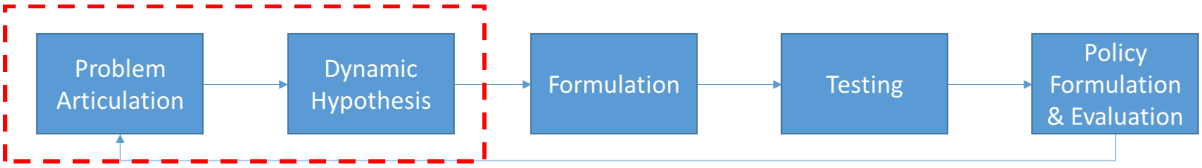

Figure 1: The SD modelling process (Sterman, 2000b) highlighting the step of focus in this study

2.1.2.Causal Loop Diagrams (CLD)

In a CLD, the polarity of the relationships between variables refers to the effect that one variable has on another. A positive ("+") link means that a change in one variable leads to a change *in the same direction* to the next variable, i.e. an increase (or decrease) in the initial variable leads to a corresponding increase (or decrease) in the other. On the other hand, a negative ("-") link means that a change in one variable leads to a change *in the opposite direction* in the next variable. These links are then considered together as closed feedback 'loops': a chain of individual linked variables that start and end with the same variable, and do not contain the same variable twice. The polarity of links within variables are important, as if there are no, or an even number, of negative links within a loop then the whole loop is considered 'reinforcing' (R) and inevitably leads to exponential growth (or decline) within a system, unless it is controlled by a 'balancing' (B) loop. This loop contains at least one, or an odd number, of negative links and is generally expected to create oscillating behaviour towards equilibrium. However, it is the relative strength of interacting reinforcing and balancing loops within the system that defines overall behaviour. System archetypes (generic structures of feedback loops) represent common behaviour patterns (such as goal-seeking, specific forms of growth or collapse), for example: "Underachievement", "Out of Control", "Relative Achievement" or "Relative Control" (Wolstenholme, 2003). These are useful in assessing if a policy intervention might be successful, or have unintended consequences. Thus, although a CLD is qualitative, and may not explicitly include every variable (as this could distract from key feedback mechanisms), it is possible to have an appreciation of the system effects from a change in any input variable. Furthermore, it is possible to consider time-lags (eg delays in effect compared to other system links) and relative magnitude of effects, when considering the links. This can be based on known evidence-based quantitative relationships or evidence, or from qualitative understanding. A CLD is useful for communicating simplified mental models that demonstrate causal relationships to policy decision makers.

2.1.3.Stock Flow Models (SFM)

A SFM may be developed from a CLD or directly from mental modes. Here, the fundamental features to capture are the stocks and flows of the system. Alongside feedbacks, these are central to dynamic systems theory. Stocks are accumulations of key entities that characterise a system at any point in time, providing inertia and memory and decoupling rates of flow to create disequilibrium dynamics. The SFM is the basis for the simulation model, and will be more comprehensive and detailed than a CLD. The simulation model, once calibrated, is used to assess sensitivities to key variables and run scenarios for impact comparison that can be used to inform policy decision making.

2.1.4.System Dynamics in Transport Studies

SD is well suited for application to transport problems offering numerous advantages over traditional approaches (Abbas and Bell, 1994). Shepherd (2014) categorised transport SD papers into various areas of application. Although a number of transport SD models consider the optimisation of fleet logistics, the largest area was strategic policy, mainly related to studying policy scenarios for improving the sustainability of transport. These models can be land-use interaction models, such as the MARS model (Pfaffenbichler et al., 2008), which has been applied across many different city regions and outputs have been used to calculate transport safety indicators as part of a wider sustainability analysis (López et al., 2012). Including MARS, many models focus on environmental, emissions or energy impacts, for example Fiorello et al. (2010) developed ASTRA, which has been used by the European Commission to link transport demand, economy, vehicle fleet and environmental impacts, but relatively few have focused on health impacts. Shepherd (2014) only identified two papers, that were related to cycling-related health (Macmillan et al., 2014) and road safety (Goh and Love, 2012).

2.1.5.System Dynamics in Health Studies

SD has been widely adopted within health studies, concentrating on various issues of public health over the last 40 years (Homer and Hirsch, 2006), such as healthcare delivery, health economics, substance abuse, infectious disease, microbiology and healthcare products (Hirsch et al., 2015). Salleh et al. (2017) identified 15 reviews of simulation modelling in healthcare including 93 studies employing SD, though Stankov et al. (2020) only identified 1 SD study in a review of transport-health simulation models. More recently, specific policies for public health promotion have been modelled using SD, however, there is little evidence on how often it is applied to policy or decision making (Currie et al., 2018, Atkinson et al., 2015).

3. Methodology

3.1. Literature Review Methodology

For the thematic literature review, we followed a similar method to two related studies. Currie et al. (2018) carried out a scoping review of SD modelling for environmental health based on established scoping review guidelines (Levac et al., 2010, Arksey and O'Malley, 2005). Following the PRISMA checklist (Moher et al., 2009), Stankov et al. (2020) reviewed simulation studies of the health impact of transportation interventions. The steps taken in this review are: 1) Identification, 2) Screening, and 3) Relevancy and Inclusion. As noted by Currie et al., we do not claim that this review is an exhaustive or complete list. The process and results are detailed in Figure 2.

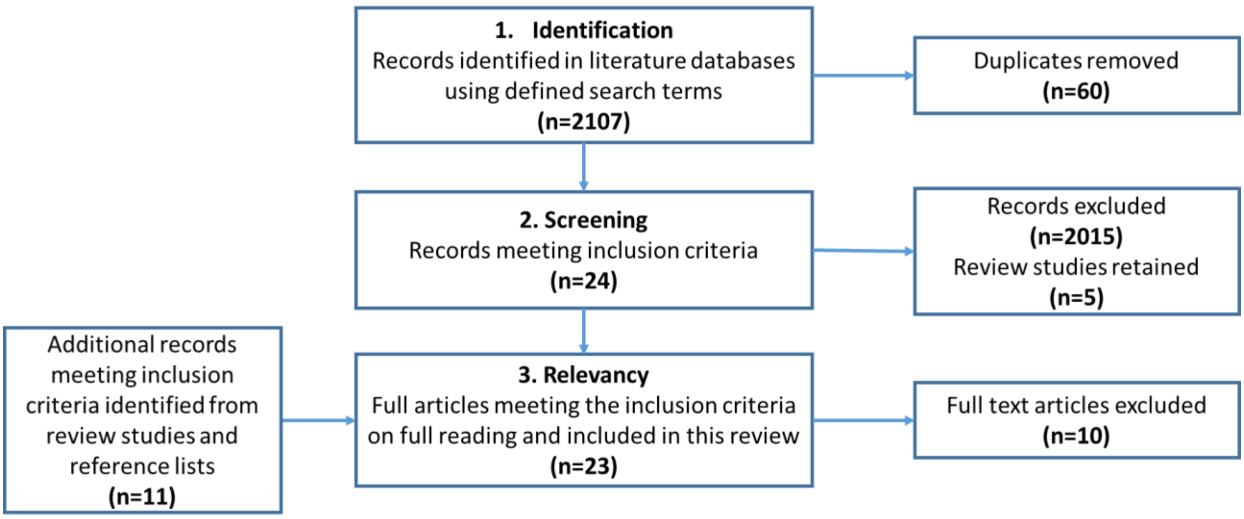

Figure 2: Scoping Review Process (Initial literature review carried out May 2019 and repeated June 2020 and October 2020)
**Google search terminated after approx. 300 records once relevance appeared to be saturated.*

3.1.1. Identification

Literature was identified through three common internet literature databases: Web of Science, Scopus and Science Direct, and the search engine 'Google' for grey literature. The search terms used were: ("transport" OR "mobility") AND ("health") AND ("systems thinking" OR "system dynamics")". The publication date was limited to the past 20 years (from 2000 onwards), in order that most recent thinking is reflected, and assuming any key works prior to this would be picked up in reference lists. For both Web of Science and Scopus these searches were limited to title, abstract and keywords, whereas in Science Direct it was possible to include full article searches, though articles were limited to subscribed research and conference papers, and book chapters. In Google the search was limited to PDF files and link summaries on results pages were screened. Only the first 30 result pages were considered as it was judged at that point that relevance had been saturated.

3.1.2. Screening

The titles and abstracts of the studies and reports identified in the initial step were screened according to the following inclusion criteria:

- The work should have a focus on the interactions between transport systems or mobility behaviours and public health
- The work must report on the development of an original system dynamics model or causal loop diagram.

In addition, for practical purposes:

- The work must be accessible to the researchers – eg through publically available sources (including subscribed databases)
- The work must be officially published (ie peer reviewed journals, conference proceedings or grey literature official reports but not including working papers)
- The work must be written in English

A small number (5) of related review papers were identified at this point, and although excluded from our review were retained for reference and scanned for suitable literature. By this stage, 38 seemingly relevant publications had been identified. Following this screening, reference lists from identified articles were considered to identify further articles, which were then subjected to the inclusion criteria.

3.1.3. Relevancy and Inclusion

In the final step of the review each of the identified articles were read in full to further assess for relevancy that may have been uncertain in the previous step. At this stage 10 articles were excluded for the following reasons:

- Neither a causal loop diagram nor stock-flow model was presented within the article (1)
- The work was too specific to a niche problem that was not deemed applicable to a generic transport-health system (2)
- Not actually using system dynamics approach (3)
- Does not explicitly include health (4)

3.2. CLD Methodology

By studying the CLDs and SFMs in the identified studies, we aim to address the first steps of the modelling process (Problem Articulation and Dynamic Hypothesis), creating a combined CLD to address the problem that policies designed to influence health outcomes related to one form of transport impact may also influence other health outcomes and transport impacts. We focused on the CLDs in the first place, as these are high-level representations of the system behaviour and identify the key variables and relationships that we are interested in. However, for those studies that also provided detail on a SFM, we considered any additional variables or parameters that may be relevant to our problem articulation. It is usual practise that CLDs are developed through literature review and/or expert engagement (Luna-Reyes and Andersen, 2003, Martinez-Moyano and Richardson, 2013). However, methods have been proposed where CLDs created by individual stakeholder groups are built upon (Inam et al., 2015, Macmillan and Woodcock, 2017). There may be concerns about combining separately developed CLDs/SFMs as they were created to address specific problems, there may be uncertainty around stakeholder perceptions (Dhirasasna and Sahin, 2019), and that some interpretation of the data may be ambiguous. However, we argue that our research question encompasses those of the identified studies and thus they can, in effect, be used as our qualitative data input in line with conventional CLD building methods (Luna-Reyes and Andersen, 2003).

4. Review of Transport-Health SD Models

There are limited examples of SD models looking directly at transport-related health. Currie et al. (2018) investigated SD studies of environmental health decision-making and policy, identifying only two within the transport sector and one further cross-sectoral study that included transport, as well as three studies that did not demonstrate links to policy decisions. Similarly, in a review of a broader set of simulation studies of health impacts of transport interventions (specifically bus rapid transit, bicycle lanes, “open streets” and cable cars), only one SD model was identified (Stankov et al., 2020) . In addition, to those identified in previous reviews (Stankov et al., 2020, Currie et al., 2018, Shepherd, 2014), a further 17 studies which employ an SD methodology to explicitly consider transport-health were identified in our own searches. Table 1 presents all 23 identified transport-health SD studies. There are five themes identified (air pollution, road safety, active transport, multiple transport impacts and noise) which all include multiple studies except noise. These themes are based around the risk factors associated with health outcomes arising from transport activities, with the exception of ‘Active Travel’, where we identified a focus on active transport modes, which merited it’s own theme due to the large body of related work. Also noted in the table are if the studies included a CLD and/or SFM (with note on where this was fully documented), and what Health Outcome and Transport Impact, relevant to our problem context, were identified in the study. We include the exact wording used by the study authors. We sought evidence of measurable Health Outcomes being considered explicitly within the CLD, SFM or associated documentation. Although these health outcomes may generally be exogenous (and not essentially relevant to the qualitative CLD), we had particular interest in how these specific measures were represented in the studies, in order to assess the trade-offs and synergies of the transport impacts on health outcomes as per the research question. Transport Impacts are the risk factors associated with health outcomes arising from transport activities. Finally, we note the main research question or objective of the studies to demonstrate their fit within our own research question. The studies are regionally dispersed, covering most global regions. Over half of the studies (14) involved offer both a CLD and fully quantified SFMs (and most (10) provide fully documented structure and equations). All but 7 of the studies include a measureable health outcome such as specific disease burdens, injuries, mortality or morbidity, which may be considered to be exogenous to a closed feedback system, though they all include the endogenous Transport Impact that influences (or is implicitly linked to) health outcomes.

Table 1: Transport-Health SD studies identified in this study (1: fully documented simulation model; 2: no SFM diagram; 3: no simulation model; 4: although some of these studies may fit under other themes (eg road safety, multiple transport impacts), as all have a focus on active transport it was deemed appropriate to group these together)

Theme	Author and Year	Location	CLD	SFM	Health Outcome	Transport Impact	Research Question / Objectives
Air Pollution	Stave (2002)	Las Vegas, US	Y	Y	No explicit measureable health outcome.	Air Quality (CO)	*"Develop policy recommendations to address the rapidly worsening and interconnected problems of traffic congestion and regional air quality in the Las Vegas, Nevada metropolitan area."*
	Stave and Dwyer (2006)	Las Vegas, US	Y	Y	No explicit measureable health outcome.	Air Pollution (CO)	*"Examine the potential effects of changes in land use and transportation planning on air quality, traffic congestion, and other quality of life factors"*
	Shahgholian and Hajihosseini (2009)	Tehran, Iran	Y	Y	"Infection rate", "Sick Population", "Cure Rate" and "Death Rate" (disease not specified).	Air Pollution (PB, HC, CO SO2, NO, NO2, Dust)	*"Which of the parameters* (population, pollutant types, weather, traffic, factories) *will have the greatest effect on pollution* (and public health) *in the next ten years."*
	Armah et al. (2010)	Accra, Ghana	Y	N	"Health risks" (not further specified) (respiratory tract infection, coughing, eye irritation specified in text only)	Air Pollution (Heavy metals, NOx, SO2 specified in text only)	*"To understand the overall dynamics of the pollution problem* (in Accra, Ghana) *by considering the road infrastructure, traffic congestion, air pollution,* (health risks) *and various stakeholders."*
	Veziroğlu and Macário (2014)	USA, China, India	Y	Y[1]	"Reduction in serious adult Illness" (People/Year) "Death Rate" (Deaths/1000 people) (disease not specified).	Air Pollution (PM10)	*"To understand how the transition to hydrogen-fuelled vehicles will be effected if the lowered health expenditures are utilized to reduce fuel costs."*
	Onat et al. (2016)	USA	Y	Y[1]	"Human health impacts, (DALY) "Adjusted life expectancy (Years) (from air pollutants and CO2, disease not specified)	Air Pollution and Climate Change (CO2, PM, Photochemical oxidants)	*"Explore the dynamic interrelationships between the environmental, social, and economic aspects of US passenger cars' sustainability impacts from life cycle sustainability perspective."*
	Caroleo et al. (2017)	Piedmont, Italy	Y	Y	Hospital admissions (Cardiovascular and respiratory)	GHG and Pollutant Emissions (CO_2, PM10)	*"A System Dynamics model to estimate the environmental health impacts of alternative market scenarios for EVs diffusion in Piedmont (Italy)."*
Road Safety	Friedman (2006)	New England Region, USA	Y	Y	No explicit measureable health outcome.	"Accidents"	*"To evaluate current road maintenance policy and its possible negative effect on accident creation."*

	Goh and Love (2012)	Western Australia	N	Y[1]	No explicit measureable health outcome.	"Crashes"	Two separate models: *"The first model is used to assess policy options so as to encourage the purchase of cars with higher safety ratings. The second model, is used to evaluate the impact of public transport policies on travel time and traffic safety considerations."*
	Alirezaei et al. (2017)	USA	Y	Y[1]	Number of injuries and fatalities	Number of fatal and non-fatal crashes Percentage of fatalities (speed related, DUI, distraction, aggressive driving, weather, other) Lives saved (seatbelt, airbag)	*"Investigating the complex interactions among* (the climate change-road safety-economy nexus) *by tracking how they affect each other over time …. to find the most efficient way(s) to increase road safety and to reduce the negative consequences of traffic* (collisions)*"*
	(Araz et al., 2020)	USA	Y	Y[1]	Drug related fatal injured drivers	Drug related crash rate	*"This paper contributes to literature by assessing the complex inter-relationships and dynamics among number of drug drivers, drugged driving laws, public transportation, drug use. treatment, traffic congestion, and other traffic-related factors and evaluating the impact of drug per se law on the number of drugged related crash fatalities"*
Active Transport[4]	Macmillan (2012)	New Zealand	Y	Y[1]	Cyclist fatal and serious injuries Air Pollution Mortality Air pollution Hospital admissions (cardiovascular, respiratory, COPD, cancer) Air pollution restricted activity days Cycling physical activity all-cause mortality	Cyclist Collisions Cycle mode share Air Pollution (PM10, CO, Benzene)	*"1. To develop a comprehensive conceptual model of the trip to work and public health that synthesises knowledge from epidemiology, communities and policy makers* *2. To develop a commuting and public health simulation model that could quantify a range of outcomes for some particular policy options"*
	Macmillan et al. (2014)	New Zealand	Y	Y[1,2]	Cyclist fatal and serious injuries Air Pollution Mortality Air pollution Hospital admissions (cardiovascular, respiratory, COPD, cancer) Air pollution restricted activity days Cycling physical activity all-cause mortality	Cyclist Collisions Air Pollution (PM10, CO)	*"to provide a system explanation for the current trend in commuter cycling in Auckland, as well as assist with identifying policy levers to turn this trend into sustained growth"*

					(by socio-demographic group)		
	Macmillan et al. (2016)	London, Birmingham, Bristol, Cambridge, UK	Y	Y[3]	Cyclist fatalities	Number of cyclists	*"Our aim was to examine whether… change in the prevalence of cycling was associated with changes in the proportion of cyclist fatalities covered by London's largest local newspaper, and in the amount of coverage per fatality"*
	Macmillan and Mackie (2016)	Auckland, New Zealand	Y	N	Pedestrian and cyclist injuries	Walking/Cycling to work, Congestion	*"We used participatory system dynamics modelling (SDM) to develop a transdisciplinary understanding of the links between commuting and "wellbeing" as a complex system, starting with a broad health framework."*
	Macmillan and Woodcock (2017)	New Zealand, London, Netherlands	Y	N	London: "Cyclist injury rate" NL: '"actual and perceived safety"	London: People cycling for some trips NL: Traffic Volumes, People cycling as main mode	*"To develop a dynamic causal model of urban cycling to develop consensus about the nature and order of policies needed in different cycling contexts to optimise outcomes."*
	Macmillan et al. (2018)	Auckland, New Zealand	Y	N	Number of walking and cycling injuries. "Health impacts (of air pollution". (no specific health outcomes) Physical and mental impacts of physical inactivity (no specific health outcomes).	Local walking and cycling Population getting recommended daily exercise. Local air quality (not specified)	*"To develop a causal theory for the relationships between active travel, and walking and cycling infrastructure* (and a) *… range of outcomes … in low-income neighbourhoods and on reducing social and health inequities.*
	Macmillan et al. (2020)	New Zealand	Y	N	Air Pollution death and illnesses (no specific health outcomes) Number of local walking and cycling injuries Proportion of people getting enough daily exercise Equity to access to healthcare services	Local air pollution (not specified) Short trips by active transport	*"Propose a complex causal theory for how the relationships between suburban retrofit and the Sustainable Development Goals are integrated, and progress dynamically over time"*
Multiple Transport Impacts	McClure et al. (2015)	Various cities	N	Y[1,2]	"Dying rate" (people/year) "Population Health" (QALY) "Disease and Injury related premature health loss" (QALYs/Year) "Disease Specific Incidence" (DALYs – child & maternal,	Crash Risk (bicycle, motorbike, pedestrian, car, public transport) Metabolic Equivalents (car, bicycle, public transport, motorbike, pedestrian) Pollution Effect (All above based on KM travelled)	*"What are the features of a land use---transportation system that optimizes the health and well-being of the population?"*

					communicable disease, endocrine, circulatory, non-transport injury, transport not-fatal, injury, transport injury death, mental health, neoplasm, respiratory, other) "Transport crash deaths" "Transport crash serious injuries"		
	Kolling J et al. (2016)	North Carolina, USA	Y	Y[1]	Premature mortalities avoided per year (no disease specified)	Physical activity Vehicle Emissions (PM2.5 and NOx) Traffic crash fatalities	*"A decision support tool for community sustainability with the proposed Durham-Orange Light Rail Project (D-O LRP) in Durham and Orange Counties, North Carolina, as a case-study."*
	Widener and Hatzopoulou (2016)	n/a (Canada)	Y	N	"Personal Health" (not further specified)	Stress, Collisions, Speed of emergency ground transportation, Physical activity, Access to health goods and services, Disease Diffusion Rate, exhaust emissions, other pollutants, road noise	"(To) *illustrate a systems perspective on the complex relationships between health and transportation … and expose potentially interesting new directions for the health and research Community".*
	Langellier et al. (2019)	Latin America	Y	N	"Health" (not further specified)	Air Quality, Duration of Physical Activity	*"To produce a single "synthesis" CLD that, in the simplest way possible, captures the major variables and feedback loops that drive change over time in food behaviours and transport in Latin American cities, as identified by participants in (the) three workshops."*
Road Traffic Noise	Recio et al. (2018)	Madrid, Spain	Y	Y[1]	>65 years cardiovascular deaths due to noise (persons/year)	Noise Level from traffic Intensity (dB)	*"The epidemic behaviour of environmental noise effects on the population over 65 years of age in the city of Madrid is examined, through its short-term association with mortality from cardiovascular causes"*

In the following sections, we will discuss the studies by theme. For the air pollution, road safety and active transport themes we present a summary of the findings and present it as a combined CLD of key variables and feedbacks that have been identified. If the reader wishes to see the original CLD/SFM they may refer to the original study, though representation is inconsistent (eg high-level or partial CLD/SFM, SFM only, use of non-standard notation). Our motivation is to create a meta-CLD addressing our research question, so we focus on the applicability of the individual studies to this, alongside some background detail on the wider context of the study. Further, as our interest is in the qualitative Problem Articulation and Dynamic Hypothesis stages of the modelling process, we assess these in relation to the best practise set out by Martinez-Moyano and Richardson (2013). We will provide brief details of any formulated simulation model but do not comment on the validity to reporting reproducibility standards (Rahmandad and Sterman, 2012).

4.1. Air Pollution Related Health

Stave (2002) presents a case study example of an engaged stakeholder group model building exercise focused on understanding the problem of traffic congestion and air pollution in Las Vegas, US. Rather than a specific health parameter, the focus is on CO (which is implicitly linked to public environmental health) with a major assumption being that "*CO is an adequate proxy for all transportation-related air quality parameters*". The 25 year simulation model was quantified and verified through data provided by the South Nevada Regional Transport Commission (such as historical and forecast transportation datasets). It was recognised that while all stakeholders could describe certain parts of the system that they were acquainted with, they only had rough understandings of the system as a whole. Only a high-level overview of the CLD is presented in the article, alongside key SFM variables and stocks, making it difficult to ascertain all of the structure that was considered. However, the author notes that there is only one (balancing) feedback loop , which is between the perceived attractiveness and the population of the region. The CO variable is determined in the model endogenously, through exogenous travel demand (trips/day/capita) and assumed relationships between vehicle stock, capacity, congestion and speed, then feeds into costs within the model, but is not involved in any feedback loop.

The same author used a similar approach, engaging with a group of high-level stakeholders to develop a model related to the above but with the goal of integrating land use, air quality and transport planning (Stave and Dwyer, 2006), The basic CLD structure was similar, but with additional feedbacks (such as from CO and congestion to the attractiveness of the area). As such, it also only considered CO under air quality (only from transport), and did not explicitly cover health, though this contributes to a factor termed 'quality of life'. The quantified model was validated against historic and projected trends and ran for 30 years, with various scenarios presented detailing the policy inputs and key model outputs

Shahgholian and Hajihosseini (2009) study the relationship between reduction in air pollution and it's related diseases within Tehran. It is not clear what stakeholder engagement was carried out to determine model structure or dynamic hypothesis. Their interest in air pollution sources was not limited to transport emissions but also considered other domestic and industrial pollutants. They did however consider multiple pollutant types (Lead, hydrocarbons, CO, SO_2, NO, NO_2, PM). In their study they developed both a CLD and a quantified SFM, and scenarios representing policies such as automobile regulation were developed. However, the study does not report the equations and input data used in the model, describe model calibration/validation or detail specific scenarios. A comprehensive CLD and SFM is provided, and unlike the other Air Pollution models identified in our review, there are detailed interactions related to the health outcomes (infection rate, cure rate, death rate, sick population), but simplified representation of transport. This said, it is not clear how the infection rate was defined – what type of diseases are considered and in what level of detail for different population subgroups.

Similar to the work previously described, Armah et al. (2010) took a SD approach to understand behaviours that lead to traffic congestion and air pollution in Ghana. They based their model on a classic 'fixes that fail' system archetype of unintended outcomes that arise from the building of infrastructure to alleviate congestion. In this case the extra capacity designed to reduce congestion (a balancing feedback loop), is also part of a reinforcing feedback loop as the extra capacity also increases car attractiveness, thus leading to a dynamic equilibrium of congestion at a higher traffic volume every time more capacity is added (Pfaffenbichler, 2011, Sterman, 2000b). They do include a specific relationship between air pollution and health risks, though it is not clear how this is characterised. Rather than engagement during problem articulation and dynamic hypothesis stages, surveys were carried out with 500 stakeholders to validate the model, but it appears no model was ever quantified. A number of health issues were included in the survey that do not appear in the CLD: distance/travel time to health facility, identified health impacts from transport (respiratory tract infection, coughing eye irritation, noise pollution), transport constraint on health, and choice of health facility by proximity. They identify that understanding urban transport-energy-environment is more complex than it appears, and failing to capture all issues may lead to policy resistance.

Veziroğlu and Macário (2014) recognise that although several SD models have been developed to understand the transition towards low emission vehicles, they do not calculate changes in health costs. Therefore, they develop a SD model for the remediation of health expenditures by transition to Hydrogen vehicles over a 50 year time period. This consists of four sub-models (population, diffusion, PM10 concentration, market utilisation), which run under different investment scenarios for USA, China and India. Their SFM is based around a simple CLD, where illness is a function of PM10 concentration, an increase in hydrogen vehicles leads to reductions in PM10, and reduced health costs from this can then be used to fund the development of the hydrogen market. It appears to be built through literature rather than stakeholder engagement. The SFM and underlying equations are provided in the paper and the model is validated using various sources of data. They conclude that the most effective strategy is to invest health expenditure savings in addition to government incentives into hydrogen vehicle costs.

Taking a systems based Life Cycle Sustainability Assessment (LCSA) approach, Onat et al. (2016) were interested in using SD to understand the sustainability impacts of Alternative Fuel Vehicles. Within this, they considered not only the direct human health impact from air pollution (particulate matter and photochemical oxidant emissions from vehicle manufacturing and operations) but also the indirect health impact from climate change arising from greenhouse gas pollutants (CO_2). The standard modelling process was followed, though there was no stakeholder engagement evident. Consisting of four sub-models (transportation, environmental, economic and social), transport demand and related health impacts are driven by GDP, employment, public welfare and population. A CLD is presented and the 9 balancing loops and 3 reinforcing loops are described. The SFM for each module is presented alongside full variables and equations. Health impacts are not explicitly defined in the model but are derived from an established impact assessment model (Goedkoop et al., 2009). The simulation model is verified using statistical analyses against real world data. They find that although health impacts from the manufacturing phase are higher for EVs and PHEVs than CVs, they are much reduced over the operating phase and ultimately over the whole life.

Similar to Veziroğlu and Macário (2014) , Caroleo et al. (2017) also considered the influence of alternative fuel vehicles on air quality related health. Though detail on how the problem and model were conceptualised is not provided in the paper, a CLD is provided which includes a reinforcing loop illustrating how the an increase in Battery Electric Vehicles (BEV) leads to a reduction in conventional vehicles (CV), and the corresponding reduction in PM10 concentration reduces cardio and respiratory hospital admissions (these are not specified in any more detail within the paper). The loop is closed by an increase in monetary savings in public health, which is then reinvested in incentives that stimulate further BEV adoption. SFM, equations and verification of the simulation model are not provided in the paper, but they find that under an 'extreme' scenario (12.7% BEV fleet share by 2030) leads to a 750% reduction in hospital admissions and €86.64m in public health savings.

In summary, from the seven papers identified that addressed the interaction between transport-related air-pollution and health in an SD model, it is evident that none took a detailed approach of both transport and health. In particular, none had detail related to the mechanisms between the transport impact and the morbidity or mortality of the disease. In Figure 3 we have combined key aspects of the CLDs presented in this section. We have identified two key feedback areas: Transport-Pollutant and Pollutant-Health. Transport-Pollutants consists of three feedback loops (2 B, 1R) interacting around the Congestion variable, that characterise the influence of capacity expansion on congestion and number of vehicles, both of which influence Pollutants emitted. This could be expanded in much more detail if different modes and trip decisions are accounted for. Through two feedback loops (1B, 1R), Pollutant-Health captures the influence of the disease burden within society arising from both local air pollution and climate change, which could be enriched by considering specific diseases and socio-demographic groups. There are seven feedback loops covering both areas. One reinforcing loop captures the potential for increased investment or incentivisation in low carbon vehicles if hospitalisation costs are reduced as suggested by Veziroğlu and Macário (2014) and Caroleo et al. (2017). The remaining six loops (3R, 3B), are represent how the influence of healthy population on travel demand are effected within the system.

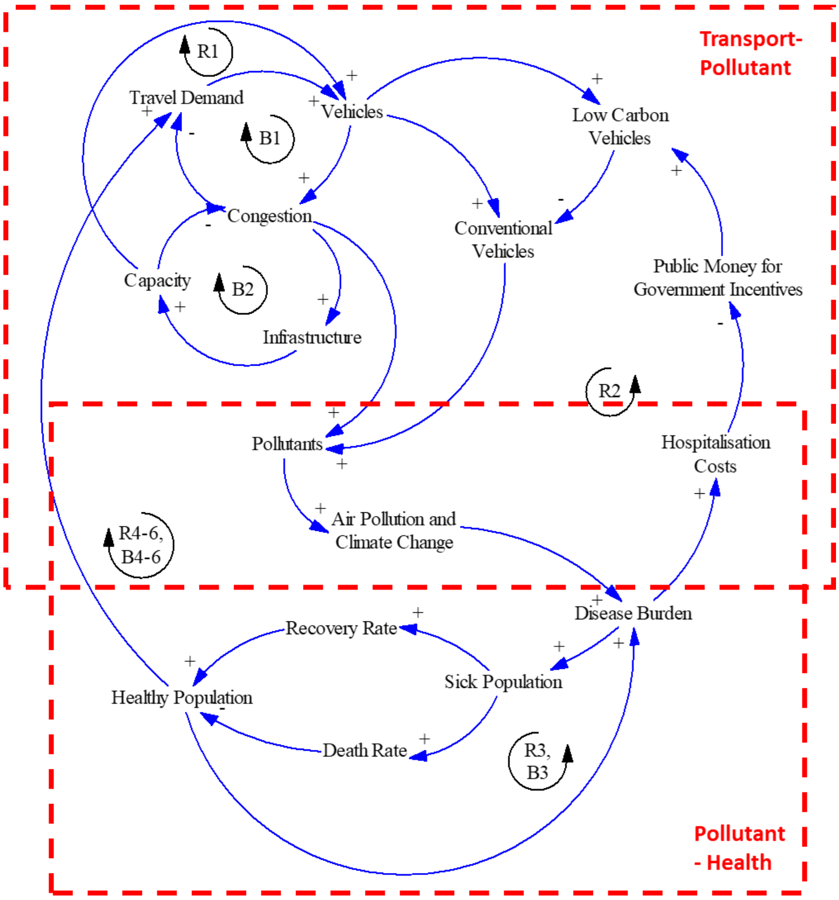

Figure 3: Transport-pollution health CLD - developed by authors from reviewed studies (Armah et al., 2010, Shahgholian and Hajihosseini, 2009, Stave, 2002, Stave and Dwyer, 2006, Veziroğlu and Macário, 2014, Onat et al., 2016, Caroleo et al., 2017)). Loop descriptions are available in Appendix.

4.2. Road safety

The possible negative effect of highway maintenance on collision rate (termed "accident" by the authors) is considered in an SD model by Friedman (2006), though they do not explicitly link "accidents" to specific injuries, fatalities or overall public health. In particular, the influence of vehicle volume on road conditions and speed is considered, and their resultant contribution to collision rate. In turn, the number of collisions influences the amount spent on repairs to the highway. The focus of the model is on highway management for the reduction of collisions rather than broader transport-related public health. They suggest that the current policy basis of repair spending to improve conditions and reduce collision rate (a balancing feedback loop) is incorrect, as infrastructure investment creates instead a positive feedback, as improved carriageways encourage higher speeds and vehicle volumes. A full SFM is provided, with partial CLDs and selected equations. The behavioural assumptions are based on literature review rather than involvement of interested stakeholders. With limited data available, the simulation model was validated through establishing a logical relationship between Pavement Service Index and accidents over a 3 year period.

Goh and Love (2012) develop two simple SD models of car safety rating policy and public transport policy impacts on safety, emphasising that SD is a good modelling approach for macro/meso level studies. Although they follow the standard modelling process, there is no stakeholder engagement. They note that low resolution of SD means it may not be appropriate for micro-level modelling (an important consideration for transport behaviours and health impacts that vary within a population). Other similar limitations recognised by the authors are lack of spatial and distributional effects. SFMs and full equations are provided for both models. The passenger car safety standards model is used to study policies to increase the stock of higher standard cars. This is validated using historic data and sensitivity testing, but the results are then incorporated in a separate cost benefit analysis (CBA) to estimate benefits of reduced collisions resulting in injuries and fatalities. In a separate model within the paper, the authors study the effects of public transport subsidies on vehicle collisions. The main feedback loops to consider here are the balancing loop between policy intervention and number of collisions, which is interlinked with another balancing loop between number of collisions and traffic volume. There is no direct link to the relationship between the number of collisions and population health.

Alirezaei et al. (2017) used SD to investigate the impact of extreme weather events caused by climate change on road safety and resultant economic impacts, identifying 5 feedback loops within the overview CLD. The problem articulation and dynamic hypothesis are developed without stakeholder involvement. The SFM is provided for 6 sub-models: Economic Losses; Economic Impact on GDP; Vehicle Safety Standards; Transportation; GHG impact on Climate; Climate impact on safety. The model was verified against historic data, and subjected to three policy levers. They found that reducing transport emissions (in the USA) had limited impact on climate change and it's impact on safety, unless extreme global emission-reduction policies are implemented globally. Reducing travel demand and increasing vehicle safety are more effective in reducing collisions than increasing fuel efficiency. They identified that the influence on collisions are infrastructure and vehicle conditions as well as driver contribution. A key feedback loop regarding collisions to consider here is that between economy and vehicle conditions, whereas climate change is involved in loops with both infrastructure conditions and driver contribution via economy and vehicle miles travelled (VMT). The health parameter here is the number of injuries and fatalities arising from vehicle collisions (in adverse or extreme weather, driving under the influence (DUI) of alcohol or drugs, distraction, speed, aggressive driving), based on published fatality/injury rates.

Focusing on DUI of drugs, Araz et al. (2020), developed an SD model to consider the impact of drug-driving on collisions and subsequent fatalities. The CLD was developed from literature and is characterised by two sub-systems of drugged driver behaviour and road environment, which were connected by population, public transit and drugged driver fatalities. Each sub-system consisted of two balancing loops and a SFM was developed that contained five stocks (non-driving drug users, drugged drivers, drugged driver fatalities, VMT and highway capacity), with parameters estimated from published data, prior research and regression-based estimation. The results suggested that implemented tighter drug-driving laws may be more effective in reducing fatalities than improving public transit provision.

Though all of these studies had specific different focuses on road safety, what is common between them is the influence of Traffic Volume on collision rate. Goh and Love (2012) and Friedman (2006) did not have explicit health parameters, whereas Alirezaei et al. (2017) and Araz et al. (2020) employed exogenous or estimated injury/death rates and risks related to collisions but no connection to overall population health. Omitting the mechanisms of climate change and details of car manufacturing, which are outside the scope of our interests, both approaches are summarised in Figure 4. This contains 21 feedback loops (15 B, 6 R), with all but one (B15) including the collisions variable and 6 involving the link between collisions and population.

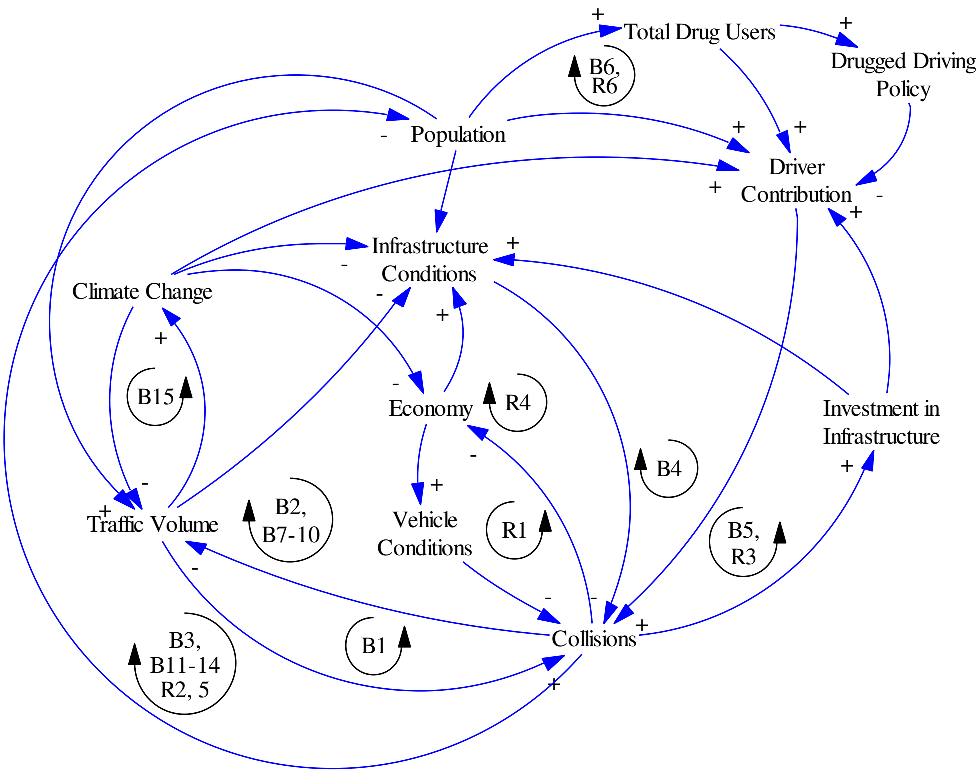

Figure 4: Combined road safety CLD – developed by the authors from reviewed studies (Alirezaei et al., 2017, Goh and Love, 2012, Araz et al., 2020, Friedman, 2006). Loop descriptions are available in Appendix.

4.3. Active Transport

A significant volume of system dynamics studies focused around active transport (walking and cycling), have been led by the same author, and indeed none were identified that focused solely on this area without this named author.

Based on the work carried out for a PhD thesis (Macmillan, 2012), Macmillan et al. (2014) understood that established models of mode shift to active travel neglected important system feedbacks that reflect the co-benefits of health, social equity and climate change mitigation. A CLD of commuter cycling and public health was developed through interviews and workshops with a variety of stakeholders (community, academic, policy) in New Zealand. The dominant loop is related to collision injuries, seen to be the biggest barrier to cycling and some loops were found to be inactive (due to local data). A SFM was quantified using governmental data-sets, evidence based data and expert opinion, and this was validated against historical data, as well as being subjected to sensitivity analysis. Full model equations are provided. The key areas were: commuting population growth, commute mode share, bicycling injury, air pollution, fuel costs and emissions, mortality due to physical inactivity. The model was found to be sensitive to assumptions around safety in numbers. Five policy scenarios were simulated over a 40 year period and considered impacts on injury, physical activity, fuel costs, air pollution and carbon emissions. The objective was to compare these policies and establish the most cost-effective, as it was recognised that there is currently little evidence on this. Unlike many studies, the simulation model incorporated significant detail related to health impacts, taking on board not just injuries but also specific disease burdens (COPD, cardiovascular, cancers and respiratory) related to air pollution (PM10, CO and Benzene) and all-cause mortality related to cycling activity (of specific socio-demographic groups).

The relationship between cyclist fatalities and media coverage thereof in general cyclist trends was the focus of Macmillan et al. (2016), building on concepts established in Macmillan et al. (2014) . Using police road traffic injuries data (‘STATS19’) and comparing to reports in a leading newspaper for the city of London, UK, then repeating for three other UK cities, the authors refined the original CLD, which included stocks and flows, but no simulation model was developed. They established that the loop “more fatalities make more stories” may not be universally relevant and fails to capture the complex role of media in cycling trends. They suggest further feedbacks related to the rise in cycling in increasing media interest and the role of the media in campaigns to increase safety investment.

Macmillan and Woodcock (2017) explored urban cycling in UK and Netherlands and compared to New Zealand. Unlike the previous paper, this study involved development of a qualitative CLD. In London, the CLD from Macmillan et al. (2014) was elaborated by identified stakeholders. In particular, we can see that risk perception has been unpacked and the importance of socio-demographic groups has been added. The only health parameter was the number of cyclist injuries, though ‘safety’ is considered. The Netherlands already had relatively high mode shares of urban cycling so CLD development was from scratch and later compared to the Auckland model. No measureable health outcomes were included, though “actual and perceived safety” is. There is a much greater focus on the comparative attractiveness to other modes compared to London and Auckland. This paper presents some interesting differences between regions but also highlights the possibility of generalisation of CLDs.

Macmillan expanded on the CLDs developed in previous work in three further papers related to a wider trans-disciplinary ‘Future Streets’ intervention project that engaged with low-income communities. In all three, literature based and participatory modelling approaches were adopted to develop qualitative CLDs, which have not so far been progressed to quantified SFMs. Macmillan and Mackie (2016) do not focus solely on active transport, but consider low carbon transitions for urban transport, specifically looking at commuting and well-being. The resultant CLD consists of 12 reinforcing loops and 3 balancing loops, with eight key loops being: active travel safety, neighbourhood sense of security, time pressure and accessibility, relative attractiveness of public transport, workplace support, environmental cultural wellbeing, ‘car culture’ & social wellbeing and transport planning participation & leadership. However, the only specific health variable included in the CLD was pedestrian and cyclist injuries, though other health outcomes are mentioned in the text as being exogenous to the CLD. As such we could have categorised this study in the ‘Road Safety’ or ‘Mixed transport impacts” themes, but have decided to include it within ‘Active Transport’ as the only explicit endogenous variable is injuries related to active transport. The influence of walking and cycling infrastructure on active travel in low-income communities is the focus of Macmillan et al. (2018). Ten loops are identified (9R, 1B) and health impacts include injuries, air-pollution and physical inactivity, but measurable health outcomes are not yet defined. Long-term results from the wider project will be used to refine assumptions within the model developed in Macmillan et al. (2014) and the broader outcomes are described in Macmillan et al. (2020). In this paper the causal theories are applied to wider considerations of the role of active travel in meeting Sustainable Development Goals, with a particular focus on equity. The CLD they develop is much more complex than the previous work, consisting of 12 reinforcing loops and 2 balancing loops. In addition to the direct transport impacts on health outcomes (risk of injuries, air pollution and exercise) a number of other influences are included, such as equity and affordability of access (to education, employment and healthcare), sense of security and social connections, access to safe public spaces and cultural wellbeing.

Figure 5 brings together the key elements common to all of Macmillan’s (and co-authors) CLDs that are most prevalent to transport-health. Some wider aspects of active transport culture are omitted in our generalisation, and in our later Combined CLD (Figure 6), we combine the broad cultural element with the variable ‘experience, awareness and acceptance’, in order to simplify yet still represent important cultural and individual perceptions and actualities. Although the clearest health impacts here are related to collision injuries (both with motorised and other active travellers), security, pollution and activity related health are included, though not within any feedback loops. Although Macmillan et al. (2014) had a detailed consideration of these in the simulation model, they were not included in the CLD, which focused on the key feedbacks (see section 2.1 on differences between CLD and simulation models). This representation shows the clear complexities that exist within active transport and health, with 36 loops contained, 21 of which are reinforcing. All loops go through either the ‘injuries and fatalities’ and/or ‘active traveller’ variables, indicating the high profile of these collisions as a health impact related to active travel given by those involved in developing these models. Although not visible in the presented CLD, it should be noted that the SFMs drawn from do consider socio-demographics and specific disease burdens.

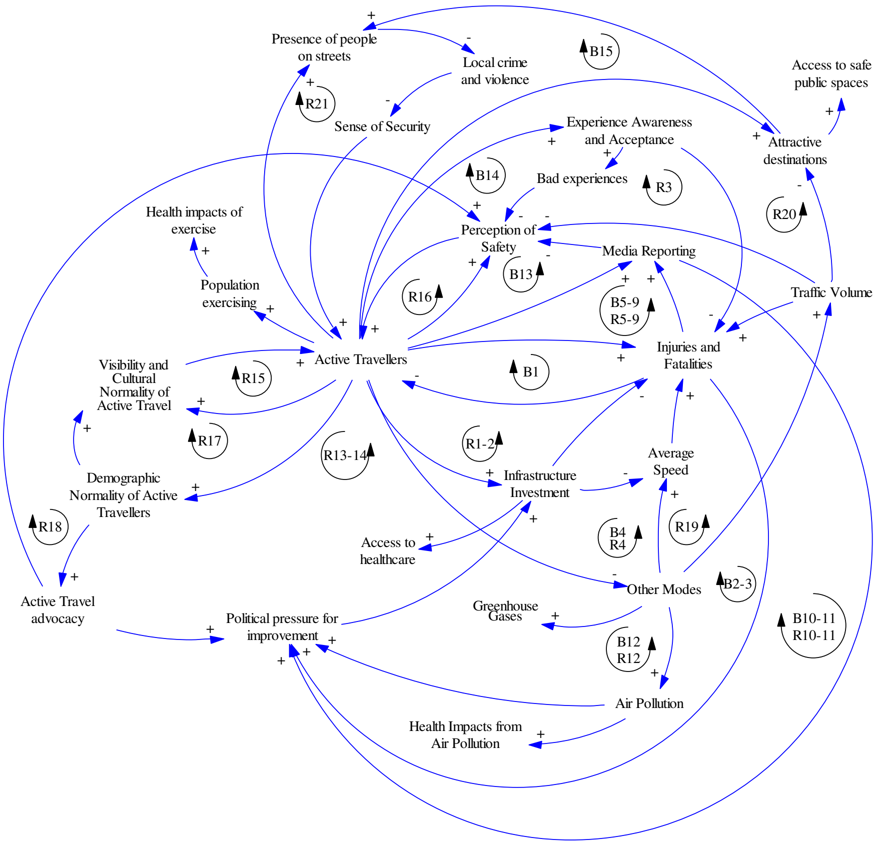

Figure 5: Combined CLD of Active Travel - developed by the authors from reviewed studies (Macmillan et al., 2014, Macmillan and Woodcock, 2017, Macmillan et al., 2018, Macmillan et al., 2016, Macmillan et al., 2020, Macmillan, 2012, Macmillan and Mackie, 2016). Loop descriptions are available in Appendix.

4.4. Road Traffic Noise

Recio et al. (2018) consider the impact on health from road traffic noise, using an SD approach. This was limited to cardiovascular mortality of over 65s as strong risk associations are already established. The relationships were established in a CLD (though it is noted that there are no feedbacks) where the variables, boundaries, structures and behaviour were determined by the authors. This was developed into a simple SFM, with stock of the population of >65s and ‘traffic intensity’. The validation process was not presented, but model equations were. Their results suggest that interventions that reduce traffic intensity would only have a short-term effect on noise pollution (and associated cardiovascular deaths), unless significant levels of electric vehicle substitution were realised.

4.5. Multiple Aspects

McClure et al. (2015) focus on road safety, health effects related to activity and pollution effects related to transport. The model was developed during an expert workshop then verified by independent experts, with the purpose of identifying the features of a land use-transport system that optimises health and well-being of the population. It is quantified and validated, including relationships between land use, transport and economic development and the impact on collision deaths and Disability Adjusted Live Years (DALYs). Neither the CLD nor SFM diagram are provided in the paper, but the model is extensively detailed in an appendix. The dynamic hypothesis developed incudes 2 reinforcing loops (the influence of wealth on transport and on health) and 1 balancing loop (the influence of transport on health). It is based around three stocks, being Population, Population Wealth and Population Health. The health stock is influenced not only by transport changes (related to population and wealth) but also access and quality of health care. The health stock is the most detailed part of the model, and includes empirically derived disease specific incidences (Communicable, Circulatory, Neoplasm, Diabetes, COPD, non-transport injury) but does not seem to relate them to air pollution. Instead a pollution effect multiplier, based on vehicle KM, is applied. However, the change in Metabolic Equivalent of Task (METS) from travel trips is also calculated, and again feeds into population health as a multipler. Mobility is quantified in terms of trips, and exposure is measured in kilometres and risk of collision (collision per kilometre). Three policy types were simulated – reducing risk, changing mode and combined. The model was first developed for Melbourne, Australia, but also applied to five other global cities (London, New York, Copenhagen, Beijing, Dehli).

In the USA, the Environmental Protection Agency developed a prototype SD model for assessing community sustainability, using a light rail project as case study. This included a module on health in relation to transportation (as well as land use, energy, water, economy, and equity) (Kolling J et al., 2016). The team followed the standard modelling process, with the problem defined and dynamic hypothesis developed at a large stakeholder meeting. They developed an initial CLD, which was quantified using local data and projections for validation and calibration. SFM, specifications and equations are provided. Scenarios were also designed in a stakeholder meeting. The transport module takes into account many factors such as speed, costs, car availability and population density, to determine VMT and its relationship to air quality and traffic collisions as well as non-motorised mode usage impact on physical health. The health module was used to quantify the avoided premature mortality due to vehicle emissions (PM2.5 and NOx), physical activity from active travel and vehicle collision fatalities. There is one feedback loop within this. Emission-related deaths were based on a nationwide US study (rather than local), physical activity from the WHO (Kahlmeier et al., 2017) and local collision data to calibrate against an assumptive relationship with VMT and collision incidence.

Though not strictly a study of a specific transport-health problem or system, Widener and Hatzopoulou (2016) explore research in transport-related health, identifying five main areas, which are:

- Indirect and direct impacts of transportation on morbidity and mortality (eg road traffic incidents)
- Direct impacts of transportation on 1) Physical environment (eg air pollution, noise, land effects) and 2) Access to healthy spaces and facilities (eg parks/playgrounds, hospitals/health care, healthy food stores)
- Indirect impacts of transportation infrastructure /networks on 1) Healthy behaviours (eg active travel, stress) and 2) Diseases pathways (eg spread through population)

They develop a CLD on how these areas interact to open up opportunities for researchers. Although the authors do not offer a quantified simulation of this (as this was not their objective), they do conclude that their CLD, which at this stage was just a high-level concept, can be expanded in any direction, reveals the importance of investigating system trade-offs and may lead to new research agendas.

The only paper identified in this study that was based in Latin America was also the only study that considered food behaviours alongside transport, recognising the influence that these areas have on health in the urban areas. Langellier et al. (2019) used community-based system dynamics methods to engage with stakeholders from 10 countries across 3 workshops with the objectives of promoting health, equitable and sustainable cities and to identify and prioritise research in that area. Separate CLDs developed in these workshops were then developed into an aggregate CLD including 10 feedback loops (6R, 4B) and fundamental dynamics discussed in the workshops, though no SFM or quantification was carried out. This CLD only contained a generic 'health' variable, with direct impacts from ultra-processed food consumption and time spent in physical activity, though the wider study considered this as chronic disease and obesity. Although not all variables and loops identified are directly relevant to this study, as they are more concerned with food behaviours, some key interactions are important to include are air quality impacts on engagement in physical activity and transport impacts on available time which in turn influences food behaviours, as well as reinforcing mechanisms witnessed elsewhere, such as safety in numbers, health impacts on public or active transport use and investment decisions.

5. A Combined CLD

Due to the complexities of the transport-health system, most scholars chose to focus on a specific part, eg transport impact or health outcome. This is demonstrated in the above review that highlights that under half of the studies considered multiple transport impacts on health outcomes.. We are interested in developing a model focusing on transport-health but with a highly grained level of detail that could provide insights into the trade-offs between policies designed to mitigate separate health impacts, which would be of value for policy-makers and complement existing health impact assessments. In particular, Although we have identified that some models do indeed go a long way towards achieving this, we note that no existing model has been proactively developed to address the problem of trade-offs. As a first stage in creating such a model, we have developed a CLD that captures the key interactions in the transport-health system that have been identified in the existing studies. This is presented in Figure 6. The reader may note that although we have reviewed 23 separate models, there are already numerous overlaps apparent. This said, our combined CLD still proves to be complex, which is indicative of the complexity of the transport-health system. There are less than 50 variables, but in fact a surprising number of feedback loops due to the complexity of connections (over 30,000 involving the variable Population Health are identified using the software Vensim^{TM}). To enhance comprehensibility, variables have been colour-coded according to four topic areas: health outcomes, transport impacts (direct and indirect), mobility behaviours (and influences on) and wider system.

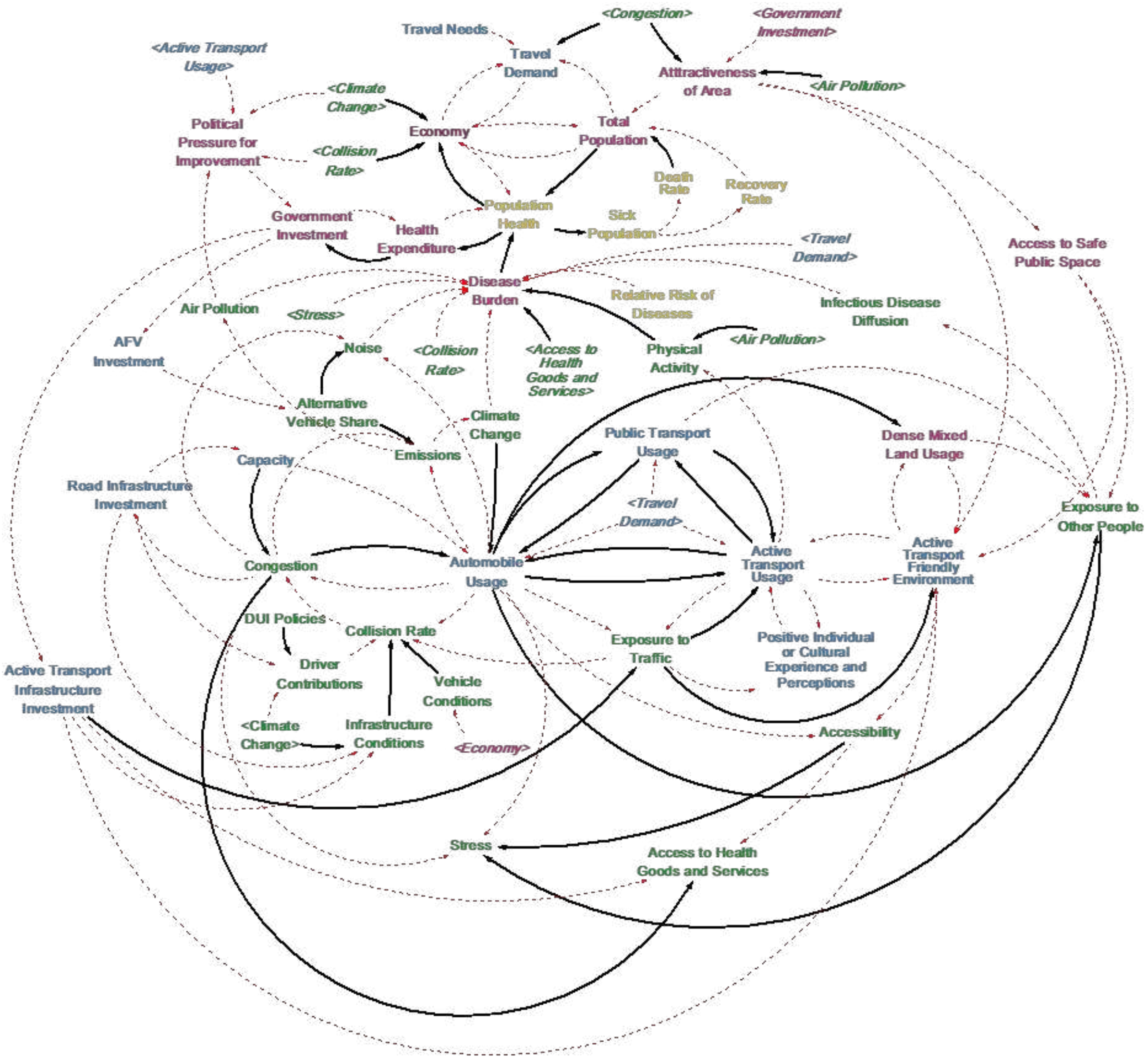

Figure 6: Combined CLD (developed by authors based on the 23 studies reviewed in this paper) ***Health Outcomes (Yellow), Transport Impacts (Green), Mobility Behaviours (Blue), Wider System (Purple), Positive (+) link (thin red dashed line), Negative (-) link (thick black solid line),*** *<XXX> (in italics) are "shadow variables", which exist elsewhere in the CLD, but are repeated closer to the effect variable of a relationship to improve the visual readability of the CLD.*

Health Outcomes (yellow) variables are required for the calculation of changes in population health that arises from specific impacts on human health from the use of transport. The key feedbacks in this group are the balancing 'death rate' and reinforcing 'recovery rate' loops between population health and total population, as well as the many loops where total population influence mobility behaviours which has subsequent feedbacks to disease burden through transport impacts.

Transport Impacts (green) variables represent the direct impacts of transport that can effect human health, and the key determinants of the impacts themselves**.** These have both balancing and reinforcing feedbacks on the health outcomes through disease burden and on mobility behaviours through the wider system.

Mobility behaviours (blue) variables represent the influential factors on travel demand and the usage of different modes of transport, which leads to impacts on human health. These have key feedbacks both between each other and on transport impacts.

Wider system (purple) variables are not directly included in the other categories, but may have an important influence on the overall system. For instance, economy has important reinforcing loops with both total population and travel demand and a balancing loop with population health, and government investment has key influences on mobility behaviours driven by transport impacts.

6. Discussion

This review, and the resulting combined CLD, was built in recognition of the problem of policies designed to influence competing health outcomes arising from transport impacts. Figure 6 is not purporting to be a comprehensive representation of the transport-health system, but captures the key variables and relationships that have been identified in existing studies. It is, however, capable of addressing our research question, as it can be used to comprehensively and qualitatively identify the complex feedbacks that exist and may be in conflict when designing transport-health policies. However, we have identified a number of important aspects that were not wholly covered in the existing studies and thus could be given more thought in future development of the combined CLD.

6.1. Transport Impacts and Mobility Behaviours

Transport systems have been extensively studied and modelled through various approaches, including SD. Mobility behaviours are detailed and complex, and may be specific to the characteristics of regions, populations and temporality. Although transport patterns, their impacts and the exposure to them by the population can be aggregated and generalised, in doing so the richness of the mechanisms that may be important for understanding feedbacks and trade-offs may be lost. Few of the studies in this review had a detailed appreciation of the transport system and included all modes of transportation and mobility behaviours across the population. As our research develops, we will draw from those studies that did give detailed consideration to these, as well as looking to what further detail may be beneficial within our research context.

6.2. Health Outcomes

We are aware that the health impacts identified within the CLD will have varying degrees of disease burden, proportional effect, time to effect and varying effect on individuals, as well as being relative to existing health conditions and underlying behaviours. Not all models in this study included explicit reference to specific health outcomes such as disease incidence, mortality and morbidity, which would be equitable to the most advanced HIAs, nor account for the differences in these between socio-demographic groups. Of those that did, there was a large variety in how this was parameterised, such as all-cause mortality, hospital admissions due to specific conditions or QALY/DALYs. Some of these parameters are indeed not endogenous to the model, moreover will be an exogenous output related to an endogenous transport impact variable. It will be critical in the development of our CLD and subsequent SFM to study the options for characterising health outcomes and identify which would be most suitable in addressing our objective of understanding trade-offs. Furthermore, we recognise that mental and social well-being may be less measurable than physical so may be under-represented in our results and there may be other interpretations of which health outcomes this included. Indeed, these were considered by a small number of studies, such as social networks/exclusion etc related to community severance (Boniface et al., 2015), but we made a decision that these were outside our boundaries, but could reconsider if we were to refine our problem articulation.

6.3. New Data and Future Technologies

All of the models reviewed in this study took a contemporary or historical view of transport-health systems. However, transport and mobility are undergoing a period of great change, arising from new technologies and changing behaviours and attitudes (Wee, 2015). Set within a backdrop of policy to encourage the use of more sustainable forms of transport, such as active and public modes, understanding the implications of these changes is paramount, as is how new data technologies (such as persuasive and self-recording apps) can influence mobility behaviours in multiple ways (such as a persuasive policy instrument or for self-reflection). Finally, the technologies are a data-source for richer, contextually specific, high-resolution finely-grained data beyond the conventional, allowing improved understanding of mobility behaviours, transport impacts impacts, and health outcomes as well as cross-sectoral trade-offs (Grant-Muller, 2017) and can be used for calibration or data input to SD models. We are confident that the inclusion of the influence of new data and technologies would not only be a novel contribution to the field but will also greatly assist in furthering the understanding of trade-offs between transport-related health outcomes.

7. Conclusion

In this paper we have recognised a need for a complex representation of the transport-health system in order to inform more holistic and equitable policy making. We identified 23 existing system dynamic models considering transport-health and from these constructed a combined CLD covering all aspects identified in the studies that could address our research question *"Where are the trade-offs and synergies between different types health impacts within the transport-health system?"* In doing so, we have completed the Problem Articulation and Dynamic Hypothesis steps of the modelling process as set out in Section 2. We began the Problem Articulation with our research question, which set out the problem (the competing influences of transport impacts on health outcomes). Through the literature review, we have confirmed why it is a problem (policies designed to influence one health outcome may also influence another) and identified the model boundary, key concepts and behavioural trends that represent it in our combined CLD. We also established that measurable health outcomes related to transport can be characterised in many ways, some of which may be exogenous to the CLD, parametrising this as Disease Burden and Population Health. The endogenous transport impacts can be classified into 6 interacting areas: Air Pollution, Stress, Noise, Collision Rate, Physical Activity, Disease Diffusion. Furthermore, it is clear that these transport impacts and health outcomes operate at different time-scales, causing difficulty in establishing an appropriate time horizon (or indeed time-step). We have however identified the key variables and relationships established in existing studies that allow us to develop a Dynamic Hypothesis, the CLD which is presented in Figure 6. There are four functional variable types in this CLD: Health Outcomes, Transport Impacts, Mobility Behaviours and Wide System. These could be improved by a more nuanced consideration of spatial, temporal and sociodemographic input. We also suggest that our CLD could be enhanced by the incorporation of new data and future technologies, which we have established could have a great influence on the transport-health system and in addressing our research question, but was not directly considered in any of the studies reviewed here.

We recognise the many strengths that the studies included in this review already have and that there was subjectivity in our interpretation of the variables and construction of the combined CLD. Indeed, inconsistencies in representation between the studies meant that comparison and combination was a difficult process. Therefore, in the next step of this research the CLD will be further refined through engaging with a varied panel of experts in the areas of mobility, public health and technology to provide their insight and feedback through a multi-stage survey process. Our research priority is to improve this through the consideration of how new data and technologies may influence the transport-health system. Experts will further contribute to issues including the relative magnitudes and timescales of impacts and feedback loops, the development of policy scenarios and the possible impacts of physical distancing policies arising from the current COVID-19 response. One well accepted limitation of SD is that traditionally operates at an aggregate level. Both mobility behaviours and health are unique to individuals. Mobility behaviours are formed by both circumstance and individual choice, and can be limited by various socio-economic factors. These same factors can be pre-determinants for health. Therefore it is important to understand the population subgroups that are relevant to be represented and how behaviours and impacts may differ between them, in order to account for social inequity within the model. We are particularly interested in a better representation of morbidity and mortality, which was not explicitly captured in many of the models in this review, but is advocated by Nieuwenhuijsen et al. (2016). The resultant CLD will then form the basis of a quantitative SD model and policy scenarios will be designed. In the development of this we will be drawing further from the studies reviewed here.

As with all models, SD is dependent on the quality of input data and is less reliable under extreme conditions or long time scales. In order to overcome such limitations, integration with other forms of models, such as HIAs, spatial models or Agent Based Modelling, may be beneficial. As would sourcing new data forms that could provide more detailed insights in mobility behaviors. Whilst our intended next stage will involve engagement with experts, a further phase could consider citizen participation, which is recommended by Nieuwenhuijsen et al. (2017).

Building on existing studies, this review and the combined CLD will have useful applications for the evaluation and development of policies related to transport-health.

APPENDIX

Loop Descriptions for Figure 3: Transport-pollution health CLD

B1	Travel Demand (+) > Vehicles (+) > Congestion (-) > Travel Demand
B2	Congestion (+) > Infrastructure (+) > Capacity (-) > Congestion
B3	Disease Burden (+) > Sick Population (+) > Death Rate (-) > Healthy Population (+) > Disease Burden
B4	Pollutants (+) > Air Pollution and Climate Change (+) > Disease Burden (+)> Sick Population (+) > Death Rate (-) > Healthy Population (+) > Travel Demand (+) > Vehicles (+) > Conventional Vehicles (+)> Pollutants
B5	Pollutants (+) > Air Pollution and Climate Change (+) > Disease Burden (+) > Sick Population (+) > Death Rate (-) > Healthy Population (+) > Travel Demand (+) > Vehicles (+) > Congestion (+) > Pollutants
B6	Pollutants (+) > Air Pollution and Climate Change (+) > Disease Burden (+)> Sick Population (+) > Recovery Rate (+) > Healthy Population (+) > Travel Demand (+) > Vehicles (+) > Low Carbon Vehicles (-)> Conventional Vehicles (+)>Pollutants
R1	Vehicles (+) > Congestion (+) > Infrastructure (+) > Capacity (+) Vehicles
R2	Pollutants (+) > Air Pollution and Climate Change (+) > Disease Burden (+) > Hospitalisation Costs (-) > Public Money for Government Incentives (+) > Low Carbon Vehicles (-)> Pollutants
R3	Disease Burden (+) > Sick Population (+) > Recovery Rate (+) > Healthy Population (+) > Disease Burden
R4	Pollutants (+) > Air Pollution and Climate Change (+) > Disease Burden (+)> Sick Population (+) > Recovery Rate (+) > Healthy Population (+) > Travel Demand (+) > Vehicles (+) > Conventional Vehicles (+)> Pollutants
R5	Pollutants (+) > Air Pollution and Climate Change (+) > Disease Burden (+) > Sick Population (+) > Recovery Rate (+) > Healthy Population (+) > Travel Demand (+) > Vehicles (+) > Congestion (+) > Pollutants
R6	Pollutants (+) > Air Pollution and Climate Change (+) > Disease Burden (+)> Sick Population (+) > Death Rate (-) > Healthy Population (+) > Travel Demand (+) > Vehicles (+) > Low Carbon Vehicles (-)> Conventional Vehicles (+)>Pollutants

Loop Descriptions for Figure 4: Road Safety CLD

B1	Collisions (-) > Traffic Volume (+) > Collisions
B2	Collisions (-) > Traffic Volume (-) > Infrastructure Conditions (-) > Collisions
B3	Collisions (-) > Population (+) > Traffic Volume (+) > Collisions
B4	Collisions (-) > Population (+) > Driver Contribution (+) > Collisions
B5	Collisions (+) > Investment in Infrastructure (+) > Infrastructure Conditions (-) > Collisions
B6	Collisions (-) > Population (+) > Total Drug Users (+) > Driver Contribution (+) > Collisions
B7	Collisions (-) > Traffic Volume (+) > Climate Change (+) > Driver Contribution (+) > Collisions
B8	Collisions (-) > Traffic Volume (+) > Climate Change (-) > Infrastructure Conditions (-) > Collisions
B9	Collisions (-) > Traffic Volume (+) > Climate Change (-) > Economy (+) > Vehicle Conditions (-) Collisions
B10	Collisions (-) > Traffic Volume (+) > Climate Change (-) > Economy (+) > Infrastructure Conditions (-) > Collisions
B11	Collisions (-) > Population (+) > Traffic Volume (+) > Climate Change (+) > Driver Contribution (+) > Collisions
B12	Collisions (-) > Population (+) > Traffic Volume (+) > Climate Change (-) > Infrastructure Conditions (-) > Collisions
B13	Collisions (-) > Population (+) > Traffic Volume (+) > Climate Change (-) > Economy (+) > Infrastructure Conditions (-) > Collisions
B14	Collisions (-) > Population (+) > Traffic Volume (+) > Climate Change (-) > Economy (+) > Vehicle Conditions (-) > Collisions
B15	Traffic Volume (+) > Climate Change (-) > Traffic Volume

R1	Collisions (-) > Economy (+) > Vehicle Conditions (-) > Collisions
R2	Collisions (-) > Population (-) > Infrastructure Conditions (+)> Collisions
R3	Collisions (+) > Investment in Infrastructure (+) > Driver Contribution (+) > Collisions
R4	Collisions (-) > Economy (+) > Infrastructure Conditions (-) > Collisions
R5	Collisions (-) > Population (+) > Traffic Volume (-) > Infrastructure Conditions (-) > Collisions
R6	Collisions (-) > Population (+) > Total Drug Users (+) > Drugged Driving Policy (-) > Driver Contribution (+) > Collisions

Loop Descriptions for Figure 5: Active Travel CLD

B1	Injuries and Fatalities (-) > Active Travellers (+) > Injuries and Fatalities
B2	Injuries and Fatalities (+) > Political pressure for improvement (+) > Infrastructure Investment (-) > Injuries and Fatalities
B3	Injuries and Fatalities (+) > Political pressure for improvement (+) > Infrastructure Investment (-) > Average Speed (+) > Injuries and Fatalities
R1	Injuries and Fatalities (-) > Active Travellers (+) > Infrastructure Investment (-) > Injuries and Fatalities
R2	Injuries and Fatalities (-) > Active Travellers (+) > Infrastructure Investment (-) > Average Speed (+) > Injuries and Fatalities
R3	Injuries and Fatalities (-) > Active Travellers (+) > Experience Awareness and Acceptance (-) > Injuries and Fatalities
B10	Injuries and Fatalities (+) > Media Reporting (+) > Political pressure for improvement (+) > Infrastructure Investment (-) > Injuries and Fatalities
B4	Injuries and Fatalities (-) > Active Travellers (-) > Other Modes (-) > Average Speed (+) > Injuries and Fatalities
R4	Injuries and Fatalities (-) > Active Travellers (-) > Other Modes (+) > Traffic Volume (+) > Injuries and Fatalities
B5	Injuries and Fatalities (+) > Media Reporting (-) > Perception of Safety (+) > Active Travellers (+) > Injuries and Fatalities
R5	Injuries and Fatalities (+) > Media Reporting (-) > Perception of Safety (+) > Active Travellers (+) > Infrastructure Investment (-) > Injuries and Fatalities
R10	Injuries and Fatalities (-) > Active Travellers (+) > Media Reporting (+) > Political pressure for improvement (+) > Infrastructure Investment (-) > Injuries and Fatalities
B11	Injuries and Fatalities (+) > Media Reporting (+) > Political pressure for improvement (+) > Infrastructure Investment (-) > Average Speed (+) > Injuries and Fatalities
R6	Injuries and Fatalities (+) > Media Reporting (-) > Perception of Safety (+) > Active Travellers (+) > Experience Awareness and Acceptance (-) > Injuries and Fatalities
R7	Injuries and Fatalities (+) > Media Reporting (-) > Perception of Safety (+) > Active Travellers (-) > Other Modes (+) > Traffic Volume (+) > Injuries and Fatalities
R11	Injuries and Fatalities (-) > Active Travellers (+) > Media Reporting (+) > Political pressure for improvement (+) > Infrastructure Investment (-) > Average Speed (+) > Injuries and Fatalities
B8	Injuries and Fatalities (-) > Active Travellers (-) > Other Modes (+) > Air Pollution (+) > Political pressure for improvement (+) > Infrastructure Investment (-) > Injuries and Fatalities
B6	Injuries and Fatalities (+) > Media Reporting (-) > Perception of Safety (-) > Active Travellers (+) > Infrastructure Investment (-) > Average Speed (+) > Injuries and Fatalities
R8	Injuries and Fatalities (+) > Media Reporting (-) > Perception of Safety (-) > Active Travellers (-) > Other Modes (+) > Average Speed (+) > Injuries and Fatalities
R9	Injuries and Fatalities (+) > Media Reporting (-) > Perception of Safety (-) > Active Travellers (-) > Other Modes (+) > Air Pollution (+) > Political pressure for improvement (+) > Infrastructure Investment (-) > Injuries and Fatalities
B7	Injuries and Fatalities (+) > Media Reporting (-) > Perception of Safety (-) > Active Travellers (+) > Demographic Normality of Active Travellers (+) > Active Travel advocacy (+) > Political pressure for improvement (+) > Infrastructure Investment (-) > Injuries and Fatalities

B8	Injuries and Fatalities (+) > Media Reporting (-) > Perception of Safety (-) > Active Travellers (-) > Other Modes (+) > Air Pollution (+) > Political pressure for improvement (+) > Infrastructure Investment (-) > Average Speed (+) > Injuries and Fatalities
B9	Injuries and Fatalities (+) > Media Reporting (-) > Perception of Safety (-) > Active Travellers (+) > Demographic Normality of Active Travellers (+) > Active Travel advocacy (+) > Political pressure for improvement (+) > Infrastructure Investment (-) > Average Speed (+) > Injuries and Fatalities
R12	Injuries and Fatalities (-) > Active Travellers (-) > Other Modes (+) > Air Pollution (+) > Political pressure for improvement (+) > Infrastructure Investment (-) > Average Speed (+) > Injuries and Fatalities
R13	Injuries and Fatalities (-) > Active Travellers (+) > Demographic Normality of Active Travellers (+) > Active Travel advocacy (+) > Political pressure for improvement (+) > Infrastructure Investment (-) > Injuries and Fatalities
R14	Injuries and Fatalities (-) > Active Travellers (+) > Demographic Normality of Active Travellers (+) > Active Travel advocacy (+) > Political pressure for improvement (+) > Infrastructure Investment (-) > Average Speed (+) > Injuries and Fatalities
R15	Active Travellers (+) > Visibility and Cultural Normality of Active Travel (+) > Active Travellers
R16	Active Travellers (+) > Perception of Safety (+) > Active Travellers
B13	Active Travellers (+) > Media Reporting (-) > Perception of Safety (+) > Active Travellers
R17	Active Travellers (+) > Demographic Normality of Active Travellers (+) > Visibility and Cultural Normality of Active Travel (+) > Active Travellers
R18	Active Travellers (+) > Demographic Normality of Active Travellers (+) > Active Travel advocacy (+) > Perception of Safety (+) > Active Travellers
R19	Active Travellers (-) > Other Modes (+) > Traffic Volume (-) > Perception of Safety (+) > Active Travellers
R20	Active Travellers (-) > Other Modes (+) > Traffic Volume (-) > Attractive destinations (+) > Presence of people on streets (-) > Local crime and violence (-) > Sense of Security (+) > Active Travellers
B14	Active Travellers (+) > Experience Awareness and Acceptance (+) > Bad experiences (-) > Perception of Safety (+)> Active Travellers
R21	Active Travellers (+) > Presence of people on streets (-) > Local crime and violence (-) > Sense of Security (+) > Active Travellers
B15	Active Travellers (+) > Attractive destinations (+) > Presence of people on streets (-) > Local crime and violence (-) > Sense of Security (-) > Active Travellers

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