Integrating Urban Road Safety and Sustainable Transportation Policy through the Hierarchy of Hazard Controls

Sam McLeod and Carey Curtis
Curtin University
sam@mcleod.id.au

This is an Accepted Manuscript of an article published by Taylor & Francis in the *International Journal of Sustainable Transportation* on 21 December 2020, available online: https://www.tandfonline.com/doi/full/10.1080/15568318.2020.1858376

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Abstract

Governments globally have endorsed Vision Zero, declaring that no person should be killed or permanently injured on public roads. Concurrently, the wider social, public health, and environmental implications of urban structure and transport choices have gained intense policy attention, as cities aim to transition towards sustainable accessibility. This is especially the case as research reveals a range of counter-intuitive road safety dynamics; many narrow approaches to road safety management appear to trigger adverse risk compensation and negative externality effects, potentially running counter to broader sustainability goals.

Recognising the urgent need to integrate road safety with broader urban sustainability measures, this paper presents a review of road safety literature using the established Hazard Control Hierarchy. In doing so, we identify and categorise opportunities to more effectively combine Vision Zero with broader sustainable accessibility policy objectives. We synthesise the literature against the Hazard Control Hierarchy to devise a framework to more effectively integrate the work of professional disciplines which shape the safety and sustainability of the urban built environment.

Keywords

Road safety; risk management; transport safety; risk transfer; urban planning

1. Introduction

Road trauma is a leading cause of death and acquired disability. Approximately 1.35 million people are killed in traffic crashes each year – a fatality every 23 seconds – making road transport the ninth largest cause of mortality worldwide (Greaves and Stanley 2016, 213, WHO 2018). Between 20 to 50 million people are injured on roads each year, exerting an estimated cost of between 1% and 5% of countries' GDP per annum (Wegman 2017). Road trauma risk is distributed unevenly and inequitably – children and the elderly are the most at risk, with poorer and minority demographic groups typically over-represented in crashes (Christie 2018, Shill 2020). Road crashes remain the leading cause of child and adolescent mortality worldwide (WHO 2018).

While the fatality rate in developed countries has generally been in decline since the 1970s (Savage 2013), progress towards road trauma reduction has been unacceptably slow. Sustainable Development Goal 3.6 - halving the number of deaths and injuries due to traffic crashes by 2020 - is almost certain not to be met (WHO 2018, xi). Many developed countries have also seen slowing or stalled progress in harm reduction, indicating the limits to what can be achieved with normative road safety initiatives (Wolley and Crozier 2018).

Road safety practice is bounded by political challenges, institutional barriers, and by the rationality of transport decision-making (Curtis and Low 2012). The implementation of progressive road safety policy is tempered by competing objectives, bounded rationality, path dependence, professional heuristics, rigid decision-making tools, and the unintended consequences of road safety measures. The full universe of transport-related risks and harms (such as sedentary disease burdens and social isolation) are poorly understood, especially at larger or more abstract spatial or temporal scales (Adams 1995). Road safety practice is commonly characterised by narrow technical specialisation (Johnston, Muir, and Howard 2013, Hebbert 2005), which can underlie potential for decisions to reflect bounded rationalities. The concept of *Bounded Rationality* is commonly applied to conceptualise sources of road user error, but is also similarly applicable to the work of professionals involved in design and management of transport systems, whose actions are inherently shaped by the institutional context in which they practice (Marsden et al. 2012). The application of measures which reduce risk is often inhibited by conventional practice and heuristics; cultural and political factors have significantly constrained the implementation of some highly effective crash reduction policies, such as reduced speed limits and travel demand management (Johnston 2010, Woolley et al. 2018, May, Tranter, and Warn 2011).

Many conventional road safety treatments result in perverse and unintended outcomes, such as road upgrades resulting in induced traffic demand and increased risk exposure (Amundsen and Elvik 2004). Many safety-driven design treatments may diminish the amenity of the urban realm (Hamilton-Baillie 2008, Hebbert 2005) and car-centric transport planning can further embed dependence on the private car within urban infrastructure and land use structures (Ahangari, Atkinson-Palombo, and Garrick 2017). Road safety treatments intended to protect motorists (particularly at intersections) may inconvenience or even escalate risks to pedestrians and cyclists (BITRE 2014, ix, Davis 1993, WHO 2013, 68). This may both offset road trauma reduction, and exacerbate the other significant public health problems posed by urban transport systems.

Car-centric urban structures have significant implications for the health and welfare of populations. Exposure to motor vehicle pollution (Bhalla et al. 2014), sedentary travel patterns and lifestyles (Stevenson et al. 2016, Frank, Andresen, and Schmid 2004), and social exclusion and isolation (Lucas, Grosvenor, and Simpson 2001) associated with car-reliant environments are themselves significant public health problems. The immediacy of road trauma may skew policy attention away from less immediate challenges, such as disease burdens associated with sedentary activity patterns, and anthropogenic climate change (Adams 1995, Davis 1993). These more abstract problems pose immense and structurally inequitable intergenerational costs of uncertain magnitude (Greaves and Stanley 2016, Lind 1995). These substantial but relatively invisible public health crises are less directly obvious than road trauma. In short, road trauma is one of the most obvious symptoms of unsustainable urban transport systems, and thus may receive disproportionate policy focus. However, recognising road safety as part of a broader sustainable accessibility paradigm presents new opportunities to identify complementary interests and design policy to realise co-benefits.

Accordingly, there is an urgent need to reconcile road safety policy with efforts to address other structural public health and environmental problems associated with urban transport (Perdue, Gostin, and Stone 2003, Racioppi et al. 2004, 20). Broader transport and city planning practice has increasingly shifted away from planning for unimpeded vehicular mobility towards providing for sustainable accessibility, through increasing the potential for more localised travel, and for travel by walking, cycling, and public transport (Curtis 2008, Cervero, Guerra, and Al 2017). However, the translation of such sustainability policies is constrained by the operationalisation of road design decisions driven by a set of professional, institutional, and political constraints, which are themselves often motivated by traffic safety concerns (Hebbert 2005, Hess 2009).

In view of these challenges, this paper aims to evaluate how the policy approach of sustainable accessibility sits within the context of seeking to achieve road safety outcomes. We use the term sustainable accessibility quite deliberately. Sustainable mobility refers to the idea of travelling by more sustainable modes of transport (away from single-occupant car use) - whereas sustainable accessibility considers that planning centred around meeting routine needs may make it possible to either not travel at all (so not be mobile in the above sense), or to achieve access through being proximate to different activities so that any travel is minimised by distance, and undertaken on foot as a priority, and if not by bicycle or public transport.

We apply the established Hierarchy of Hazard Controls framework at the macroscopic scale of urban transport governance to classify, critically review, and prioritise a broad range of crash reduction measures detailed across the available research literature. The Hazard Control Hierarchy (HHC), also known as the Hierarchy of Hazard Control or Risk Control Hierarchy, is a risk management framework, originally developed in the 1980s and 1990s, aimed at informing decision-making in the design and management of dangerous industrial systems (Main and Ward 1992, Manuele 2005). The HHC prioritises management methods which are most effective at decreasing the likelihood of adverse events occurring (Figure 1).

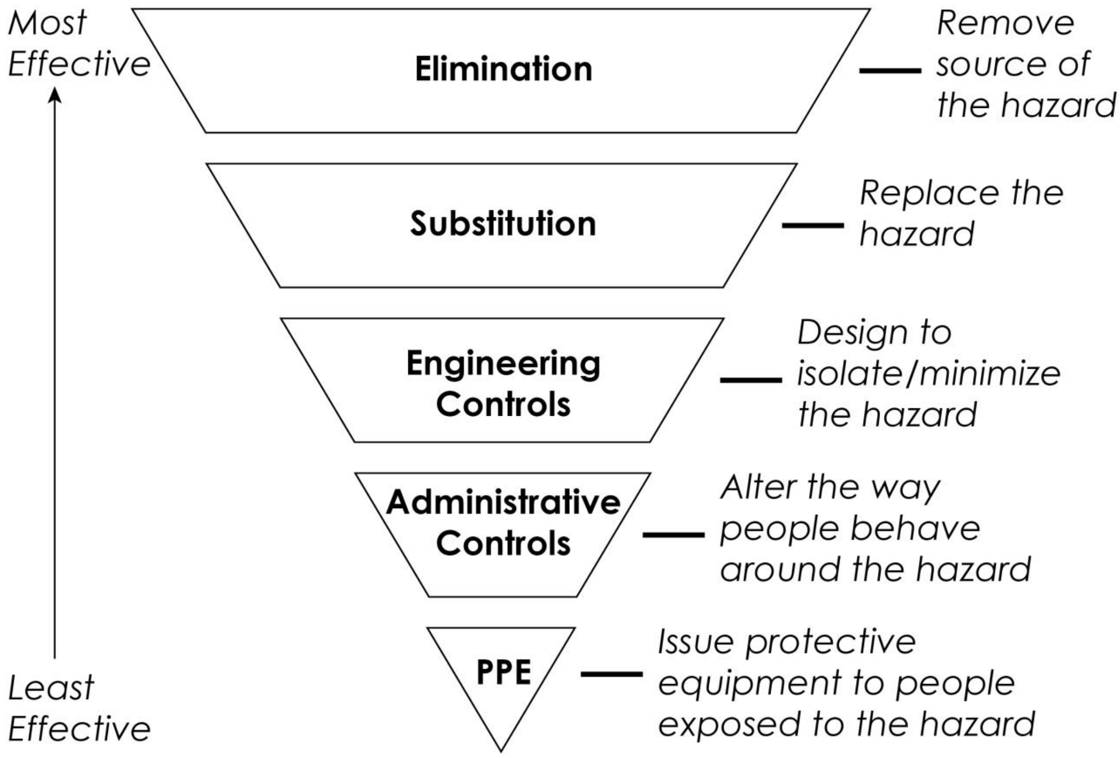

Figure 1: HHC Adapted from Manuele (2005, 36).

The HHC has been adopted in some technical standards, such as the ANSI/ASSP Z590.3: *Prevention through Design: Guidelines for Addressing Occupational Hazards and Risks in Design and Redesign Processes* standard (Manuele 2014, 317). To date, use of the well-established HHC risk management approach in conceptualising road safety policy within peer-reviewed research has been limited, while many other conceptual frameworks have been adopted and adapted in road safety practice (see Hughes et al. 2015). While there has been some use of the HHC in public discourse on transport planning issues[1], use of the hierarchy in road safety literature has to date been bounded within narrow engineering contexts(McTiernan and Rensen 2016, Turner et al. 2016, 14). This paper therefore

[1] See https://www.treehugger.com/bikes/what-hierarchy-controls-and-what-does-it-have-do-bikes.html

applies the HHC at the wider planning scale to critically draw together and examine the literature for how forms of urban governance can integrate road safety within a wide range of urban management practices. In doing so, we conceptualise the re-framing and integration of road safety policy within a broader transition towards sustainable accessibility through prioritisation of policy measures in line with the HHC.

2. Research Approach

This research commenced with a review of the interface between urban planning and road safety. The search approach utilised iterative queries of major databases (including Google Scholar, Scopus, and Web of Science), extensive backwards and forward snowballing (Van Wee and Banister 2016), and broader internet searches for grey literature, using Google Search. Various combinations of safety terms (“Road Safety”; “crashes”; “road AND accident”; “safe system*”) were paired with planning related phrases (“urban planning”; “land use”; “sustainability”; “travel demand management”; “transport planning”; “accessibility”; “mobility”; “public transport”; “freight”; “cycling”; “walking”; “driving”) using the AND search operator. Results were scanned and selected for inclusion in a database; papers were not excluded by date, but only papers written in English were reviewed. Coverage of the research literature using these search engines was evident through the consistency of the results obtained from each database.

To ensure coverage, the authors also retrieved published research and reference sources from their own existing collections of literature, and through requests for suggested readings (published studies and technical reference materials) from academic and practitioner colleagues (Van Wee and Banister 2016, 284). From this process, the HHC was identified as a relevant framework through which to structure the analysis, so extensive searches using phrase variants (including “hazard control”; “risk control”; “hazard hierarchy”, and each category of the HHC) were used to collect supporting literature relating to the framework. No equivalent academic source linking road safety to the HHC in detail was identified. In all, 196 sources were compiled and reviewed, of which 144 are cited in this manuscript[2].

This paper aims to explore the policy challenges of managing the total set of risks associated with transport at the macroscopic scale, rather than individual risks that might exist at specific contexts or locations. Taking the ISO 31000 (2018) definition of risk as “the effect of uncertainty on objectives”, we conceive of “risk” as being the total potential for harm to the public resulting from urban transport systems - which may be realised in the form of crash events, or indirect impacts upon wellbeing.

[2] A list of all 196 sources identified has been provided as a supplementary dataset accompanying this paper.

In order to conceptualise the manner in which a range of macroscopic volumes of risks may be transformed by policy, we incorporate established concepts in risk theory to the discussion. Accordingly, we adopt the terminology of Litman (2018) and Elvik et al. (2009, 645), dividing risk into internal risks (risks to the individual traveller), and external risks (risks which the traveller imposes on other parties as a result of their travel). Risk compensation refers to a potential effect whereby people will take greater risks if they perceive an activity as being less dangerous – which can erode the practical effects of safety improvements (Adams 1995, Elvik et al. 2009). Each of these concepts are explored in more detail through section 4 of this manuscript.

3. Theoretical Context

Road safety policy has long been characterised as reactive and narrowly problem focussed. Conventional attitudes towards road trauma in many countries has reflected a utilitarian position, placing responsibility almost entirely on individual road users (Shill 2020, 17), and accepting the road trauma problem as a trade-off made in exchange for the benefits of vehicular mobility (Kamerud 1983, Noland 2013). This "mobility-safety trade-off" has long persisted in road safety theory. In some countries, the term "road toll" commonly describes a price of human life paid for the mobility benefits of road networks. The "statistical value of a human life" has long been a controversial concept to enable monetary evaluation of safety decisions (de Blaeij et al. 2003, 216, Greaves and Stanley 2016, Hauer 1994), which are still commonly evaluated against monetised benefits of travel (Transport and Infrastructure Council 2016). At the other end of the spectrum, some crash prevention approaches have focussed on reducing the incidence or rate of *all* crashes, without a specific focus on minimising the harm to people which results from them.

In contrast to this, the central principle of the Vision Zero approach is that it is entirely unacceptable that any person is killed or permanently injured by transport systems, with all parties involved in developing urban transport systems sharing responsibility for its safety (Johansson 2009, Wegman 2013). Vision Zero is codified in International Standard ISO 39001:2012, which specifies a management system for road safety, based on *Safe Systems* principles (ISO 2012). The basis for this approach is the known limit of kinetic energy a human body can withstand, with any safe system designed to prevent exposure to crash violence beyond this limitation (UN Road Safety Collaboration 2010).

The long-term objective preventing all fatalities or severe injuries is to be achieved through five "pillars" of the Safe Systems framework (UN Road Safety Collaboration 2010), which are:

- Road Safety Management (governance, target setting and monitoring, coordinated decision-making);
- Safer Roads and Mobility (improved transport system design);

- Safer Vehicles (improved vehicle safety features);
- Safer Road Users/Road User Behaviour (ensuring driver competence, removing of unfit drivers); and
- Post-Crash Response (ensuring rapid access to quality emergency care)

Safe Systems thinking acknowledges that human error is inevitable – and thus the entire transport system should be "forgiving" so that errors do not result in severe injury or death (Wegman and Aarts 2006). Multiple levels of protection, from each pillar, work to prevent severe outcomes even if another fails. Table 1 illustrates common treatments associated with the Safe System pillars within the HHC, illustrating the overlap between pillars, a heavy orientation of typical approaches at lower levels of the hierarchy, and the potential limits of policy approaches which apply a limited set of interventions.

Table 1: Macro-level Safe System Measures against the HHC

Level	**Related Safe System Pillar**				
	Road Safety Management (Governance and management systems, policy coordination)	**Safer Roads and Mobility (Road network design)**	**Safer Vehicles**	**Safer Road Users**	**Post-Crash Response[1]**
Elimination -Remove/ eliminate the hazard	● Policy measures to eliminate certain travel (e.g. telecommuting); policy integration				
Substitution - Replace the hazard	● Policy to incentivise public transport	● Providing bus lanes and cycle tracks, discouraging private car use	● Encouraging motorcyclists to drive vehicles		
Engineering Controls - Isolate people from the hazard	● Road network design standards	● Installing roundabouts, grade separation	● Automatic braking systems		
Administrative Controls - Change the way people behave	● Coordinated road rules	● Speed limits	● Lane departure warning systems	● Drink driving law enforcement	
Personal Protective Equipment (PPE) - Protect people with individualised safety equipment	● Vehicle design standards	● Crash barriers	● Vehicle crashworthiness, air bags	● Bicycle helmets, high-visibility clothing	

[1] *Post-Crash Response* does not fit within the HHC as it is only effective once a hazard has resulted in a crash event. Source: The authors, hierarchy adapted from Manuele (2005)

The performance of governments in implementing Safe Systems is extremely difficult to measure - little information for the total expenditure against individual Safe Systems pillars is available. This is because road safety costs and expenditure are often indirect, contained within other infrastructure or policy funding, and are borne by a wide set of agencies. While Safe Systems philosophy aims to place harm prevention at the forefront of all road management decisions, the way it is operationalised is often still problem-focused. For instance, the reduction of internal risks to motorists is frequently the primary focus of road safety practices (Shill 2020). Road safety decisions – particularly those which relate to road engineering – may remain limited to specialist domains of practice (Featherstone 2004). While Safe Systems is recognised as current best practice in road safety management, it is bounded within a frame of road safety which may not precisely align with other public health problems and negative externalities of urban transport. Several such critical policy issues include: the environmental externalities of urban transport (especially those which relate to air pollution and global warming, habitat destruction, and noise); human health outcomes (both in terms of exposure to pollutants, injury from crashes, psychological wellbeing, and levels of physical activity); local urban amenity; the total quantum of land and resources consumed by cities and urban transport systems; and the distributional effects of risk management approaches. These are detailed in Table 2, and discussed in order of each level of the hierarchy through section 4.

Table 2: Policy issues and management approaches within the HHC

Control Method	Definition at the level of urban transport	Scale and Impact on Hazard/Risk	Impact on Environmental Externalities (Pollution, noise)	Impact on wider human health and amenity	Impact on land and resource consumption	Potential for risk transfer
Elimination - Remove/eliminate the hazard	How much total transport occurs?	Widespread - can eliminate (or partially eliminate) exposure to all risks of transport	Reduction proportional to magnitude of eliminated transport	Reduced exposure to pollutants and noise	Reduce total land and resource consumed for transport system	Practically none
Substitution - Replace the hazard	What is the mode share of all transport?	Widespread – substitution of modes can minimise total internal and external risk exposure	Significant reduction or transformation	Reduction of exposure to harms, potential for increased physical activity/wellbeing	More land and resource efficient modes prioritised	Total risk reduced by lowering external risk, though some potential for increased internal (individual) risk with increased active transport
Engineering Controls - Isolate people from the hazard	How safe is the design of the transport system equipment?	Localised to site or vehicle – design can manage or transform specific crash risks (usually specific to particular modes/road users)	Highly dependent on site-specific intervention selection and design (e.g. roundabouts may have unintended consequences on active travel, new highways may induce more risk exposure, grade separation may harm local amenity and increase land consumption)			Significant potential for increased exposure, may also trigger reverse substitution towards driving
Administrative Controls - Change the way people behave	How do applicable rules govern behaviour of individuals operating equipment?	Variable - road rules and regulations to manage risk profile	Generally minimal, depending on type of regulation. Can have unintended consequences (e.g. banning pedestrians from roads may reduce active travel).			May be some effects of complacency/ compensation – behaviour within rules may be erroneously be presumed to be safe
Personal Protective Equipment (PPE) -Protect people with individualised safety equipment	How does physical equipment reduce forces experienced during a crash?	Individual - Provide "last line" of defence against the worst consequences of the risk	Effectively none, except when crashes occur			Potential for greater external risk through risk compensation effects

Source: The authors, hierarchy adapted from Manuele (2005).

4. The Hazard Control Hierarchy as a Basis for Policy Integration

As we have established, the sustainability of urban transport system consists of a vast set of inter-related policy problems, of which road safety is of critical concern. The challenges of policy-making at the city or regional scale are immense, as is the complex policy environment which may influence road safety outcomes. The HHC provides a basis for collating theory and evidence of the benefits and shortcomings of measures, in order to inform the prioritisation of measures. This section provides an overview of each level of the hierarchy, presenting theory and empirical evidence outlining how measures may have significant effects on other objectives of urban sustainability. Through this review, we highlight how the framework may facilitate more integrated thinking about the inter-related safety and sustainability issues.

4.1 Elimination

The HHC theorises that completely eliminating the activities which pose risks has the greatest potential to reduce harm. In the context of urban transport systems, we conceptualise elimination in terms of total magnitude of realised transport demand (and therefore transport-related risk exposure). Travel Demand Management (TDM) has frequently been raised as a primary measure to prevent crashes by reducing total road travel and exposure to associated crash risks (Brindle 1984, May, Tranter, and Warn 2011, Litman and Fitzroy 2018, Lovegrove and Litman 2008). Policy measures to eliminate exposure to travel risks may do so through encouraging substitutes for transport (such as telecommuting), or through reducing overall distance travelled (such as through trip consolidation, carpooling, trip chaining, and through planning strategies to reduce trip lengths).

While aiming to reduce overall travel may be politically challenging, measures to reduce distances travelled by car, and to discourage car ownership, appear successful in reducing crash incidence (Elvik et al. 2009, 1056). Through ex-ante and ex-post analysis, Green, Heywood, and Navarro (2016) find that the introduction of the London congestion charge was associated with a reduction in the rate and total number of crashes occurring within and around the congestion charge zone. In a comparative analysis of all states across the US, Ahangari, Atkinson-Palombo, and Garrick (2017) find that vehicle ownership per population and vehicle distance travelled (VMT/VKT) are the strongest variables correlated with fatalities. Similarly, Ewing and Dumbaugh (2009) find that reduced vehicle distances travelled in urban areas is strongly associated with reductions in crash deaths. Urban structures and policies which promote selection of regular travel destinations located closer to home (such as mixed use zoning and greater land use densities) may reduce road trauma by decreasing road travel risk exposure (Litman and Fitzroy 2018). Indirect or accidental TDM measures, such as increases in fuel prices (Grabowski and Morrisey 2004), economic crises (Wegman 2017), or increased unemployment (OECD/ITF 2015) also yield reduced crashes through reductions in vehicle distance travelled and changes in road user mix. Methods to decrease the overall consumption of road transport therefore tend to have significant beneficial safety effects, and can be used to redirect resource uses to alternative transport choices.

Trips vary significantly in their utility value perceived by the traveller, and both individuals and firms adapt their behaviour to the range of trip options available. Demand for travel is often latent (not realised due to lack of suitable transport options), and can be induced, through an increase in road capacity being made available (Clifton and Moura 2017). Congestion, which varies the actual cost of travelling, can therefore significantly impact on travel choices, as individuals may reroute, reschedule, change mode, or cancel trips. Relationships between traffic congestion and crash frequency, type, and severity risks are complex, and research into these dynamics remains inconclusive (Noland and Quddus 2005). Little research has explored policies to simply *defer* travel to periods of potentially lower risk (Litman and Fitzroy 2018). Policy-makers must also consider the objective of supressing travel on the accessibility of those with already limited means to travel (Vigar 2002, Martens 2006). Structuring cities to promote shorter trips on less resource-expensive modes may significantly improve accessibility for disadvantaged groups while also reducing long-distance vehicular commuting (Scheurer, Curtis, and McLeod 2017).

Travel Demand Management should form one primary road trauma risk control mechanism, among the broader range of crash reduction methods available. However, the need for travel will always exist, and urbanised areas configured to support reduced vehicle travel typically achieve a proportion of safety benefits through mode substitution, rather than complete trip suppression. As this mode shift involves a transfer rather than elimination of risks, these strategies should be considered as falling on the next category of the HHC.

4.2 Substitution

If risks cannot be eliminated, it is desirable to substitute severe risks with safer alternatives, provided that all other factors are equal. Substituting modes with greater crash risk to safer ones should form a major component of any strategy to reduce road trauma (Shalom Hakkert and Gitelman 2014, 143, Whitelegg and Haq 2006, 93). In contemplating such strategies, the risks of transport activity can be divided into internal risks (risks to the traveller), and external risks, to which others are exposed (Litman 2018). For instance, while walking and cycling are comparatively vulnerable modes of transport (in terms of internal risk), they impart extremely low levels of risk to other road users (external risk), as outlined in Table 3. From a policy perspective, specifically minimising external risks should be the primary aim both on equity grounds, and since such modes are significantly more resource-efficient.

Table 3: Relative Internal and External Risk of Transport Modes

Mode	Internal Risk (Vulnerability)	External Risk (posed to others)
Walking	High	Extremely Low
Cycling	High	Very low
Motorcycling	High	Low
Commuter and Freight Rail	Extremely Low	Extremely Low
Private Car/light goods vehicle	Low	High
Public bus	Very low	Moderate
Heavy goods vehicle	Low	Very high

Note: All rated on a per passenger or payload mass basis. Source: The authors.

The relative risk of modes differs when compared against the number of trips made, the distance travelled, and the time spent travelling, which should be carefully considered when evaluating substitution strategies (Brög and Küffner 1981). Efforts to reduce private vehicle travel typically increase the desirability of alternative modes, and practitioners should be mindful to consider the specific travel reduction and mode substitution effects of TDM strategies.

4.2.1 Public Transport

Public transportation involves extremely low risk of passenger harm, and investment in safe public transport systems has been identified as a road trauma reduction strategy (Truong and Currie 2019). Generally speaking, the total personal (internal) safety risks of travelling on public transportation is about an order of magnitude lower than private vehicle travel (Litman 2018, Savage 2013). The mixed-mode nature of taking public transport results in a highly variable risk exposure to individuals across an entire journey – with pedestrian first and last trip legs being most risky (Elvik et al. 2009, 1063, Evans and Addison 2009, Morency et al. 2018).

Increases in public transport utilisation may reduce the total quantum of both internal and external risks. However, the risk profiles of public transport modes differ between system and trip characteristics, and in how such risks are defined and measured (Evans, Frick, and Schwing 1990, Wulff 1996). Buses may pose comparatively high external crash risks (to others) on a per vehicle distance basis (Litman and Fitzroy 2018, 30). This rate is offset by the minority share of public transport in most cities globally, and in the *per passenger distance* risk reduction effect of concentrating many travellers into a single vehicle (Redelmeier 2014). Bus and passenger rail have similar safety records, and are broadly the safest forms of surface passenger transport (ATSB 2005, Savage 2013, 14).

The degree to which public transport is promoted and adopted as a specific road safety measure varies significantly. In 2015 the United Nations explicitly agreed to "provide access to safe, affordable, accessible and sustainable transport systems for all, improving road safety, notably by expanding public transport" within the seventeen Sustainable Development Goals (Wegman 2017, 69). ISO

39001:2012 contains only a passing mention to public transport as one element of the importance of safe journey planning (ISO 2012, 23). Similarly, the 2011-2020 Global Plan for the Decade of Road Safety mentions the importance of mobility management and modal diversity within the *Safer Roads and Mobility* pillar, though the associated performance indicators relate mainly to the physical road network, with none specifically relating to public transport. Historically, it has been common for road safety plans to entirely lack mention of public transport (Chen and Meuleners 2011), which may be partly due to road safety policy sitting with road planning agencies or police departments rather than planning or transportation planning institutions. Failures to implement Travel Demand Management and achieve mode shift as major road safety policies have persisted for decades (Brindle 1984), especially while road safety has been conceptualised as being only a sub-field of traffic engineering.

4.2.2 Freight

The economic imperative to move large quantities of goods results in high-mass vehicles with an incentive to travel quickly – producing massive kinetic energy and therefore crash risk (Elvik 2010). This quantum of traffic is difficult to eliminate, except where supply chains can be configured to host many activities at a single site. Since elimination is usually not practical, substitution is therefore a major strategy in managing crash risk posed by freight. Freight rail exposers others to risks at generally low rates, with risk mostly concentrated at level crossings (Miller, Douglass, and Pindus 1994), or for trespassers (Savage 2013, 12). Forkenbrock (2001) estimates that freight rail has approximately one third of the total crash costs per tonne kilometre compared equivalent truck movements, while analysis of Australian data by Laird (2005) suggest that the ratio is 1:20 in favour of rail. Rail fatality rates per train distance travelled among Australia and the UK are about one tenth of those in the US used by Forkenbrock (ONRSR 2017), illustrating significant variation between contexts. Policy measures to encourage freight rail are therefore likely to realise safety dividends. Similarly, transport of commodities by isolated conveyor or pipeline systems is preferable as associated road safety risks are largely eliminated. City planning has a considerable role to plan in shaping the selection of land used for freight and logistics uses (Wagner 2010), especially since providing new freight rail and bulk commodity infrastructure becomes increasingly difficult as industrial precincts become surrounded by urbanisation.

4.2.3 Walking and Cycling

Contemplating road safety for pedestrians and cyclists needs to both protect them from harm, and to encourage more travel by active modes. Increasing walking and cycling can significantly reduce road trauma (Elvik 2000, 2009a, Elvik et al. 2009, Flügel et al. 2015, Litman and Fitzroy 2018). Increasing participation in these modes has significant flow-on safety benefits. Jacobsen (2003) presents compelling evidence across the United States and Europe that the risk of motorists colliding with pedestrians or cyclists decreases as there are more pedestrians or cyclists using the road. This “safety in numbers" effect has been further documented by Robinson (2005), Elvik and Bjørnskau (2017), Murphy, Levinson, and Owen (2017), and others.

While the spatial distribution of this effect is not well-understood, Clifton, Burnier, and Akar (2009) find that locations within Baltimore which exhibited improved pedestrian permeability and bus access had notably lower pedestrian crash rates. The health benefits of walking and cycling significantly outweigh the associated crash and air pollution exposure risks (De Hartog et al. 2010, Tainio et al. 2016). Improved walking and cycling facilities can enhance accessibility for isolated people. Pedestrian and cycling trips can be unrealised due to fear of travel, such as the perceived danger of crossing roadways (Mindell and Karlsen 2012), or the risk of crime along poorly designed pathways (Lucas, Grosvenor, and Simpson 2001). Therefore, designing cities to facilitate walking safe from crime needs to be recognised as an interlinked component of road safety.

Neighbourhoods suited to walking facilitate routine travel activities with very low private vehicle travel (Litman and Fitzroy 2018), and can support local commerce (Cervero, Guerra, and Al 2017). Planning to facilitate walking and cycling is likely to have significant broader injury prevention benefits as participation increases. Active transport also has significant protective cardiovascular and mental health benefits (Bhalla et al. 2014), is extremely space and resource efficient, can contribute to social inclusion (Lucas, Grosvenor, and Simpson 2001), and has minimal direct environmental externalities.

4.2.4 Ridesharing and Autonomous Vehicles

Autonomous vehicles (AVs)[3] may hold some promise in reducing crash rates, primarily through reductions in driver error. More than 90% of crashes and 40% of fatality crashes in the US are attributed to driver impairment or distraction (Fagnant and Kockelman 2015). The risk appetite of autonomous vehicle control algorithms will have a significant influence on crash rates; as roads are likely to be shared by AVs, human drivers and non-motorised road users for the foreseeable future. Risk-aversive driving behaviour by AVs might shift vehicle-pedestrian dynamics, facilitate pedestrian impunity, and implicitly enforce renewed pedestrian priorities in central city precincts (Millard-Ball 2018). Implicit in the complex moral judgements of AVs, driving algorithms must make decisions involving some uncertainty about the possible errors of other road users (Epting 2018). AVs also introduce other crash causes, including software error and manipulation (Bhavsar et al. 2017), and tragic instances of these have been widely reported as trials continue.

[3] We have classified mode shift to ridesharing and autonomous vehicles as substitution, as the ownership and control of the transport provision is structurally different to private vehicle ownership, though in some cases alterations in risk might be more accurately classified as engineering controls.

Both ridesharing and AV technologies may partially increase crash risk exposure through increasing vehicle distance travelled – and particularly for additional vehicle distance travelled associated with empty running. Barrios, Hochberg, and Yi (2018) have recently assessed that the additional traffic volume associated with new ridesharing services has resulted in an increase of approximately 2-4% in fatal crashes in American cities. However, the availability of ridesharing also has safety effects by increasing travel options for intoxicated people who may otherwise attempt to drive (Greenwood and Wattal 2015). Even if ridesharing and AVs have some safety benefits, an increase in total traffic is likely to result in some increase in risk exposure - especially where the error of other road users remains. The flow-on implications and risks of AVs are complex and deserving of further analysis (Milakis, van Arem, and van Wee 2017), while policy-makers should remain clearly focused on ensuring that strategic transport objectives lead the governance of new forms of mobility (Legacy et al. 2019).

4.3 Engineering/Design Controls

Engineering controls do not eliminate the total risk associated with transport; they transform the nature of risks in the context or location where they are applied. Redesigning systems to significantly alter risk exposure is desirable when a hazard cannot easily be eliminated or substituted. The major elements of transport systems which may be engineered to be safer are vehicles and roads. However, we contend that only vehicle engineering features which specifically *prevent* the occurrence of crashes (such as anti-lock braking and early collision warning systems) are engineering controls. Measures which reduce the severity of harms experienced by occupants in a crash are PPE (refer section 4.5).

Recognising that both travel and human error are inevitable, the *Safer Roads* pillar of the Safe Systems is commonly applied to eliminate severe injury by designing roads which reduce the crash forces imparted on road users (Wegman and Aarts 2006, Johansson 2009). Re-engineering road environments on this basis can yield significant accident reductions (Elvik et al. 2009, Wegman and Aarts 2006), though policy-makers must be cognisant of the likely crash reduction in risk exposure *per vehicle*, and the overall total number of severe crashes (Knott 1994), particularly as new traffic volumes can increase total exposure and offset benefits. Contrary to common conjecture, efforts to reduce congestion may therefore not necessarily substantially improve safety (Noland and Quddus 2005). Improving road capacity can result in the realisation of previously latent demand – termed “induced demand” (Clifton and Moura 2017). This represents a significant issue, described in detail by Amundsen and Elvik (2004), who find that induced volumes of traffic generated by new and upgraded arterial roads can offset reduced per-vehicle crash rates by increasing total crash risk exposure. Further, road projects can catalyse the relocation of destinations to sprawling, car-oriented environments, thereby reducing accessibility by other modes, perpetuating car dependence, and increasing exposure to crash risk. Thus, even when planning for both safety and mobility, the effect of improved mobility can erode actual safety benefits. Many safety-oriented street engineering measures (such as preventing trees being planted close to road edges) also have negative impacts on local amenity and on the experience of the street for pedestrians (Hebbert 2005).

4.3.1 Design and Speed

Since the 1930s, cities has increasingly been engineered to minimise time taken to travel between destinations (Patton 2007, Urry 2004). Travel speed is the critical prerequisite to crash incidence and severity, because is directly coupled to the build-up of kinetic energy, which determines the violence experienced in a crash (Cameron and Elvik 2010, Wegman and Aarts 2006, 14). Crash risks increase non-linearly with greater speed (Elvik, Christensen, and Amundsen 2004). Design speed thus has considerable safety implications. Across the last five decades, evidence of a significant but counter-intuitive phenomena has emerged whereby more generous roadway engineering (and other safety measures) can impede safety outcomes (Dumbaugh and King 2018). This occurs through the facilitation of higher travel speeds, and increased risk-taking (Peltzman 1975, Rudin-Brown and Jamson 2013, Shalom Hakkert and Gitelman 2014). This "risk compensation effect" theorises that people have a risk "appetite", and will adjust their behaviour to take greater risks when they feel protection offered by safety measures - countering the intended benefits of measure (Adams 1995, Elvik et al. 2009). However, the magnitude of risk compensation offsets is controversial, and difficult to measure (Dulisse 1997) and predict (Vrolix 2006). Given the above, it is unsurprising that forecasting the crash reduction benefits of design treatments is extremely challenging (Noland 2013).

Effective design and engineering can exploit risk compensation effects by creating road environments which engender perceptions of risks, encouraging lower travel speeds, and therefore reducing kinetic energy and crash severity. Design can encourage less risky driving through reliance on physics, geometry, and perception, rather than the ongoing resources involved in active enforcement (Woolley et al. 2018). This approach aims to temper the hazard of apparently "safe" driving conditions for motorists. Engineering streets to instil uncertainty of the right of way to facilitate active, low-speed negotiation has been used to considerable effect in a number of "shared space" projects (Karndacharuk, Wilson, and Dunn 2014, 208, Hamilton-Baillie 2008). Similarly, low impact speeds at roundabouts underpin their relative safety performance for motorists (Dumbaugh and King 2018), though they can inhibit walking and cycling across intersections. Further, the presence of tighter geometry and more numerous potential minor impact features (such as street furniture, trees, lighting) along the edges of urban roads - termed "edge friction" - appears to be associated with reduced road trauma, potentially due to the speed cues these attributes suggest to drivers (Ewing and Dumbaugh 2009). These less "forgiving" environments seek to enforce practical speed limits through engineered crash *rate* risk, lowering *severity* risk, therefore resulting in overall improved safety performance. This approach has been termed "self-explaining design"(Martens, Compte, and Kaptein 1997), and has been demonstrated in many innovative urban environments globally (Charlton et al. 2010).

A similar approach with potential for safety improvement are *road diets*, where urban thoroughfares are reconfigured to reduce through travel lanes in favour of improved walking, cycling, or public transport facilities. This more balanced approach to providing for all modes of transport within the street shows significant safety benefits (Chen et al. 2013, Harkey 2008, 21, Noland et al. 2015), and often results in reduced local traffic volumes, offering a potential reduction in risk exposure through eliminated or substituted travel. Safety-related local traffic calming measures appear to be associated with increased rates of walking and cycling among children (Carver et al. 2010), and pedestrians more broadly (Elvik et al. 2009), increasing substitution. Hence, dedicated facilities such as segregated bicycling facilities should be provided because they have very direct (engineering control) benefits (Wegman, Zhang, and Dijkstra 2012), and wider risk reduction effects through increased cycling participation (substitution). The broader benefits of speed limit and traffic volume reductions - including noise and pollution reduction, health benefits, and broader amenity improvements - can be powerful motivators to build public support for transformation of major roads within cities (McLeod and Curtis 2019).

Due to their interaction with land use and activity patterns, transport systems at any scale are not conventional systems – they are only one component of the infinite complexity of cities. Traditional thinking to view and manage road, active transport, freight transport, and public transport networks in isolation from each other is a simplistic approach and creates a barrier to reducing the number of people killed or seriously injured while travelling. Road agencies manage immensely large road networks, which comprise mostly of established assets which change only very slowly through incremental decisions (Patton 2007, Woolley et al. 2018, 5), making adaption inherently incremental task. An integrated approach to managing the complete transport system is necessary if Vision Zero is to be achieved.

Transport network design and land use dynamics are closely tied (Jones 2018). Broadly, denser development with more constrained and fragmented road network form appears to support lower incidence of very severe crashes. In analysis of crashes in 24 cities in California, Marshall and Garrick (2010) identify an association between increased road intersection density and reduced risk of fatal or severe crashes. Similarly, Graham and Glaister (2003) find that the rate of pedestrian fatalities is lower in extremely dense city precincts, potentially due to increased congestion and lower vehicle travel speeds. Urban traffic engineering has long focussed on removing pedestrians and other obstacles away from the travel of vehicles (Hebbert 2005, 43), which appears contrary to the both the safety in numbers and risk compensation effects. Progress to update technical guidance and standard practices to integrate risk compensation and other risk offset effects has often been regrettably slow (Noland 2013), particularly as the implications of these theories may sit uncomfortably against conventional design thinking. Such design can be hampered by competing design criteria – for instance, the type of vehicle roads are designed to cater for can inadvertently result in designs which facilitates risk compensation for other road users. In these cases, designers must often balance accommodating the bulky geometry of larger vehicles – particularly freight, large buses and emergency access vehicles (Chiarenza et al. 2018) – with road designs that encourage cautious driving by all vehicles. All involved in the design of the street shouldconsider the broad implication of every design decision against these effects.

4.4 Administrative Controls

Rules and regulations can manage human activity to manage risk exposure. Highly successful administrative controls in road safety include speed limit enforcement, impaired driving policing, improved driver training and licensing, vehicle inspections, and other road use regulations (Elvik et al. 2009). However, the enforcement of such rules requires constant input of resources, may be eroded by lax enforcement (Shill 2020) and can be challenging to coordinate, particularly in low-income countries.

The apportionment blame for traffic crashes by legal systems is an important – though often neglected – area of road safety policy (Whitelegg and Haq 2006). Jurisdictions can reform laws which assign liability for crashes to deter specific risk-taking behaviours (Cunningham 2008). Additionally, "administrative" land use planning and building development codes can partly contribute to crash reduction through supporting elimination and substitution measures (Cervero 2002). Urban design policies and regulatory processes can substantially influence engineering controls, through: appropriately scaling land available for roads and streets; limiting the availability of parking to discourage driving; and designing a suitable private built form interface to present edge friction and thus encourage lower vehicle speeds (Curtis 2005). This underlines that road safety policy must exist across a broad range of domains rather than within an individualised speciality practice.

4.5 Personal Protective Equipment

Providing those at risk with Personal Protective Equipment (PPE) is the lowest control category in the HHC, because failure in any single factor in the use of the equipment is likely to result in uncontrolled exposure to the hazard (Manuele 2005). Any vehicle design measure which is intended to reduce injury once a crash has occurred (such as seat belts, air-bags and crumple zones) could be considered to be PPE. PPE within vehicles can be protective through reducing forces experienced by car occupants, though such complex and heavy equipment is not practical for cyclists and pedestrians. The crash reduction effects of new vehicle technologies are, at least initially, enjoyed mostly by wealthy motorists, who can more frequently upgrade their vehicles to newer models (Elvik 2009b, 825). Separate to the *Safer Vehicles* Safe Systems pillar, the *Post-Crash Response* pillar aims to reduce the incidence of death and disability resulting from crashes by providing best-practice medical care to victims (Mohan et al. 2006). While this is indeed critical, it is ultimately always preferable that injury does not occur, so that the need for this care is prevented.

Use of PPE is again likely to be vulnerable to risk compensation effects. The literature detailing risk compensation effects towards vehicle safety measures is extensive, but findings are varied (Vrolix 2006). Drivers' perceptions of their own vehicle safety can influence risk-taking behaviour (Adams 1995, 155). One classic example of PPE, bicycle helmets, are very controversial because they appear to supress participation in cycling (Fyhri, Bjørnskau, and Backer-Grøndahl 2012, Robinson 2006, Wegman, Zhang, and Dijkstra 2012), reducing health benefits. They also appear to alter risk perception and risk-taking by drivers, potentially offsetting protective benefits (Adams and Hillman 2001). However, evidence of any risk compensation effect varies (Esmaeilikia et al. 2019). Broadly, reduced rates of cycling can precipitate reduced demand for bicycle facilities, furthering the decline. Such unintended effects underline the complexity of managing risk, and the potential for unintended consequences when applying what, prima facie, appears to be an effective injury reduction measure.

5. The Implementation Challenge

Road safety is a shared responsibility (Haddon 1980), and transcends the conventional divides between built environment, transport, and health professionals (Hebbert 2005). The next frontier of road safety measures are likely to challenge conventional practice, sow controversy, and require coordinated leadership to implement (Johnston 2010, May, Tranter, and Warn 2011). While Vision Zero has established a principled stance that any death or irreversible injury is unacceptable (Wegman 2013), the complexity of broader risk substitution, transformation and exposure effects is sorely deserving of policy attention. Efforts to achieve road safety are inextricably linked to other issues of public welfare - including significant questions of transportation equity, environmental crises, and the social implications of transport systems (Pereira, Schwanen, and Banister 2017). These are inadequately examined within a purely crash-reduction focus. All the while, mobility culture and path dependence continue to act to restrain novel practice to design safer cities (Curtis and Low 2012, Urry 2004).

Through examining road safety policy measures identified within the literature against the HHC framework, we illustrate the policy complexity of aiming to achieve Vision Zero whilst also managing other urban policy goals. We propose the HHC as a basis for prioritising treatments (Table 4). While road safety and urban planning may be regarded as quite disparate, the HHC highlights the potential to align planning across spatial scales to manage both road safety and the other externalities of urban transport identified through this manuscript.

Table 4: Hierarchy of Integrated Urban Transport Policy Measures

Control Method	Example Measure	Spatial Scale	Typically deployed in Safe System approaches?	Impact on other Sustainability Objectives
Elimination	TDM; Road pricing	Very broad (cities, states)	Less common	Significant or transformative
	Incentivise car-pooling			
	Land use policy			
Substitution	Increase public transport mode share			
	Increase cycling participation			
	Increase walking participation			
	Increase freight rail and bulk handling mode shares			
	Increase safe ridesharing/safe AV utilisation			
Engineering Controls	Designing roads to reduce speeds	Medium (individual roads, intersections, vehicles)		
	Designing roads to encourage mode shift			
	Active in-vehicle crash prevention systems (ABS, early warning devices)			
	Re-engineering road environments			
Administrative Controls	Road rule enforcement			
	Assignment of legal liability for crashes			
	Driver fitness, driver education, managing intoxication			
	Vehicle inspections			
Personal Protective Equipment (PPE)	In-vehicle technology (seat belts, airbags, etc.)	Extremely small (individual vehicle components)		
	Helmets, protective clothing		More common	Marginal

Source: The authors.

5.1 Decision-Making Interfaces

Planning decision-making is constantly subject to normative bias, individual heuristics, politicisation, and the influence of external vested interests (Legacy 2016, Macmillen and Stead 2014, Priemus, Flyvbjerg, and van Wee 2008). At the macro scale, structural decisions about city form and transport economics which may *eliminate* or *substitute* travel risks may be hampered by political and economic interests, requiring leadership which marshal support built upon the entire scope of related benefits (May, Tranter, and Warn 2011).

The complexity of the interface of road safety and broader planning goals requires critical examination of the ethics and tools used to support decision-making. Utilitarian decision-making tools, such as cost-benefit analysis (CBA), are often used to evaluate road safety proposals within a ‘rational’ quantified and monetised framework (Elvik 2001, Næss 2006, van Wee 2012). Such methods require simplistic modelling of risk transformation, and often fail to fully integrate the complex social, environmental, and urban form implications of proposals, especially if those effects are difficult to measure or meaningfully forecast (Hickman and Dean 2018). CBAs are typically subject to significant error (Flyvbjerg 2009); recent ex-post analysis of CBA for road projects in Australia reveals significant shortfalls of actual safety benefits compared to those forecasted (BITRE 2018). The selection of safety engineering projects on cost-benefit forecasts may be structurally inequitable, as expenditure allocated to safety spending with the highest cost-benefit ratio tend to favour projects which reduce risk for car occupants - even though these crashes have much better survival rates than crashes involving pedestrians, cyclists, and motorcyclists (Curtis and Low 2012, 106, Elvik 2009b). CBA may insufficiently integrate risk offsets associated with induced demand (reverse elimination) and mode shift towards vehicles (reverse substitution) that may arise through engineering controls. Projects selected through CBA may prioritise subsets of the public who already enjoy relatively high mobility (Martens 2006), and the standard practice of discounting of future benefits has also been criticised as running directly counter to principles of intergenerational equity (Lind 1995).

These problems demonstrate the need for broader and deliberative decision-making processes aligned through wide integration of knowledge. Road safety should not be viewed as one domain of expertise, but as one of many important knowledge areas required to synthesise effective urban policy. The entangled nature of transport-related problems, and the significant cross-domain benefits associated with elimination, substitution, and engineering controls aligned with the sustainable accessibility concept should enable an alliance-building approach to realising change (Næss 2001, Legacy 2016, Shalom Hakkert and Gitelman 2014).

5.2 Prioritising Decisions using the HHC

While the Safe Systems approach is recognised as best practice in road safety policy, it can only be achieved through contemplating the highly interdepend nature of managing transport and land use challenges within cities. Decisions about the prioritisation of measures need to be made. Decision-making tools need to be applied only through a strong understanding of many policy objectives and priorities (Elvik 2001), and a wide scope of knowledge (Te Brömmelstroet and Bertolini 2009, Davoudi 2015). This belies the importance of countering institutional and professional fragmentation of the governance of land use and transport in cities (Curtis and Low 2012), and strongly supports a deliberative approach to making decisions based on agreed ethical principles and values (Hauer 1994, McLeod and Curtis 2019, Wegman 2017). Sharing insight and conjecture to identify and explore the ethical implications of shifting the risks of movement within cities should be a critical part of this (Zietler 2008). Knowledge frameworks, including the Safe Systems approach and HHC outlined in this paper, are extremely valuable in facilitating interdisciplinary integration and advancing evidence-based practices (Hughes et al. 2015), especially within professions which have to cope with inherently bounded knowledge.

6. Conclusions

This paper has outlined a hierarchy of strategic road safety approaches at different spatial scales, through a review of the literature detailing the complex dynamics which influence the efficacy and external effects of such measures. In doing so, we have outlined implications for each category of control measures, and highlighted the impacts that such measures have on other externalities of transport, and on broader issues of urban sustainability and transport equity. Through examination of the literature, we find a compelling rationale for integrating road safety within more holistic decision-making approaches, and more actively prioritising measures through the HHC - especially at macroscopic planning scales.

This paper has made a novel contribution in illustrating the inter-relationship of urban health, sustainable accessibility, and road safety, through the use of an existing theoretical framework to demonstrate a wider scope of policy measures which may better address objectives relating to each. Our novel use of the framework provides a compelling basis for prioritising urban planning approaches which systematically manages both road trauma risks, and other negative impacts of transport. In exploring Safe Systems approaches against the HHC, we highlight a pressing need for re-evaluation of how professionals seek to prevent road trauma within cities. In concluding this review, we reflect upon the complexity of integrating Vision Zero principles within the planning and decision-making processes that shape urban environments. While safety within cities has been the focus of this paper, research to apply the HHC for rural contexts may present additional opportunities to improve policy and practice.

The complex risk dynamics of road safety measures are highly variable and context-dependent, compounding the challenge of translating research into policy application (Wegman 2017). However, when framed within broader questions of planning for safe, equitable, and sustainable transport, clear findings emerge to support an approach aligned with the HHC framework. Approaching Vision Zero through the HHC framework results in broad alignment between road safety risk reduction and other urban policy objectives, which may enable the application of controversial or difficult road safety policies which hold great promise in preventing road deaths. Further research which illustrates the boundedness and fragmentation of current policy approaches, and the potential for their integration using the HCC or other risk management frameworks would be of significant value.

All professionals involved in road safety must confront the uncertainty and complexity of managing transport risks, especially since such questions of decision-making reflect moral values and potentially competing models of ethics. Structural factors may counteract safe outcomes; normative standards can be extremely slow to change (Noland 2013). Professional practices may revert to path-dependent routines and methods (Curtis and Low 2012), and decision-making tools and processes may institute inequitable values and ethical systems (van Wee 2012). Sustainable accessibility integration, while difficult to achieve in practice (Jones 2018, May, Tranter, and Warn 2011), holds much promise in improving living conditions and minimising environmental impacts of urbanisation.

In evaluating road safety within the Hierarchy of Hazard Controls, we posit that the mobility-safety trade-off is deeply flawed, since many road safety measures fundamentally improve accessibility and equity. Thinking about mobility and safety as mutually exclusive is entirely inadequate in understanding the total effects of different policy decisions. This false dichotomy is also ignorant of the immense opportunity to align road safety as a central part of sustainable accessibility, such as through prioritising policies using the HHC. Road safety should not sit separately to land use and transport planning - it deserves integration through all city-building processes. By recasting transport safety as a core component of city planning, we may both accelerate the vision of zero casualties, and progress the complex transition towards urban systems of truly sustainable accessibility.

Acknowledgements

Sam McLeod wishes to thank Adam Wilmot for his insight and enthusiasm for road safety, which inspired this research. This research received no specific funding, but this paper was developed while Sam McLeod was providing consultancy services to the Road Safety Commission and Main Roads WA.

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