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The Importance of Adopting a Safe System Approach—Translation of Principles into Practical Solutions

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Abstract: The 1990s saw the emergence of the Swedish Vision Zero and the Dutch Sustainable Safety philosophies on road safety. At the time, both were considered somewhat radical and ambitious departures from the status quo. The principles that underpinned both the Dutch and Swedish philosophies were combined into an internationalized form, now known more widely as the Safe System. The Safe System came to attention early in the 2000s, when formally adopted by a number of countries committed to preventing severe road trauma. The Safe System defines a new way of thinking about road safety compared with what had commonly been used around the world in the decades before its conception. The Safe System strives to eliminate death and severe injury from the world's roads. It also underlines the importance of the safe management of kinetic energy and system-based design that seeks to ensure that crashes are prevented or, at worst, crash forces fall within the threshold of human tolerance to severe injury. Once this thinking is embraced by the system designer, new solutions begin to emerge, and existing designs can be seen in a different, more insightful light. The process of transitioning to the ambitious, ethically based philosophy of the Safe System, as a means of addressing the risks of using our roads, has not happened smoothly or quickly. Practitioners have had difficulty in translating the philosophy and principles of the Safe System into practice. It is hoped that by providing examples of the differences in decisions made under Safe System principles when designing and operating roads, large gains will be made toward the lasting elimination of road trauma. A major focus of the discussion is on the Safe System-aligned design of infrastructure, coupled with vehicle operating speeds, while also recognizing the contributions to risk reduction that can come from improved human performance and the evolving safety features and technologies of modern vehicles.

Keywords: safe system; infrastructure; speed; vehicles; targets; road trauma

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Citation: Corben, B.; Peiris, S.; Mishra, S. The Importance of Adopting a Safe System Approach—Translation of Principles into Practical Solutions. *Sustainability* **2022**, *14*, 2559. https://doi.org/10.3390/su14052559

Academic Editor: Elżbieta Macioszek

Received: 18 January 2022
Accepted: 20 February 2022
Published: 23 February 2022

1. Introduction

A recent publication by the World Health Organization [1] reported that global deaths from road traffic crashes increased to 1.35 million a year in 2016, that deaths in road crashes are the leading cause of death for those aged 5 to 29 years, and that 93% of those deaths occur in low- and middle-income countries. Estimates of survivors who sustain severe injuries are an additional 20 to 50 million annually worldwide [2–4]. The United Nations General Assembly [5] has called for a 50 percent reduction in road deaths by the year 2030. This is clearly a casualty pandemic that needs urgent attention.

Measures for addressing road safety crashes have been developed over the last 60 years. In particular, the "*Haddon Matrix*" approach, developed by the late William Haddon Jr. [5] in the 1960s, stressed the need for adopting a more scientific dose/response approach, where crash causation by crash sequence can be singled out for specific attention.

While the *Haddon Matrix* approach has been successful when used to identify and prioritize developing road safety interventions, a more systemic Vision Zero philosophy has been called for more recently by bodies such as the United Nations General Assembly and others [5–7]. This paper sets out to outline the Vision Zero philosophy and the associated Safe System approach to develop research, interventions, and policies. Specific examples of the potential benefits of Safe System over other approaches, and recommendations for further improvements in road safety are addressed.

By examining data and the circumstances of several major crash types that characteristically lead to death and serious injury, this paper seeks to demonstrate, through robust scientific evidence of effectiveness, that large and lasting reductions in severe road trauma can be achieved by applying the principles of the Safe System to road design, rather than traditional, incremental approaches. It is also reasoned that an approach based on managing the kinetic energy of vehicles is scientifically sound, since such an approach is founded in the laws of physics, specifically the laws of kinematics that describe the motion of objects. Safe System also applies scientific knowledge on the biomechanical thresholds for injury to humans when kinetic energy exchange occurs in road crashes of various types.

1.1. Vision Zero

Vision Zero was first legislated by the Swedish Government in October 1997 [7]. The philosophy behind Vision Zero acknowledges that crashes will continue to occur, but ultimately, no event which occurs on the road transport network should result in death or permanent injury [8]. Since its inception, the Vision Zero concept has been accepted globally, including by countries in Europe, U.K., North America and Australasia. Vision Zero is an ethical philosophy that prioritizes road safety improvements across four fundamental safety principles [8]:

1. Humans are fallible and the errors they make on the road can result in vehicle crashes that generate excessive crash forces;
2. Humans have a limited biomechanical tolerance and their inability to withstand high crash forces means they may be severely injured or killed in a crash;
3. Designers, builders and users of the road transport system have a responsibility and moral obligation to anticipate human fallibility and prevent or minimize the injury which can result from human error and/or poor design;
4. The road transport system is strengthened by the focus on safe behaviors, safe vehicles, safe roads and safe speeds, in such a way that if one part of the system fails, then the road user should still be protected by other parts of the system and no harm should result to the road user.

The Safe System approach has been active in Australasia for over a decade, during which time jurisdictions have implemented it to varying degrees and with varying success. The National Road Safety Strategy (NRSS) in Australia and New Zealand's Road to Zero road safety strategy are based on the Safe System approach to improving road safety [9]. The approach adopts a holistic view of the road transport system, including the importance of understanding interactions among roads and roadsides, travel speeds, vehicles and road users. Safe System caters to all road users, namely drivers, motorcyclists, passengers, pedestrians, cyclists, and commercial and heavy vehicle drivers. It adopts a long-term view of Vision Zero, recognizing that people will always make mistakes and these mistakes may have consequences which result in a crash, but the road transport system should be forgiving such that nobody should experience death or serious injury as a result.

1.2. Safe System Approach

While Vision Zero is the fundamental philosophy that ultimately aims for zero deaths from transportation, Safe System is a methodological approach for embracing the Vision Zero pillars in research, policy and implementation [7,8]. Given that road crashes are often caused by a combination of contributory factors, Safe System systematically identifies ways in which the four pillars of Safe System can work together to prevent crashes and minimize crash outcomes [10].

As shown in Figure 1, the Safe System approach focuses on four elements or pillars for the prevention of serious injuries, which can result from a crash, namely (i) safe people (behavior), (ii) safe vehicles, (iii) safe roads and roadsides, and (iv) safe speeds. Safe System is essentially an energy management approach based on the kinetic energy ($KE = {}^1/_2mv^2$) of the vehicle and the biomechanical tolerance of the crash victim(s). It specifies that for a Vision Zero outcome, the energy transfer from the vehicle to the victim cannot exceed a value beyond which serious injury is likely to occur.

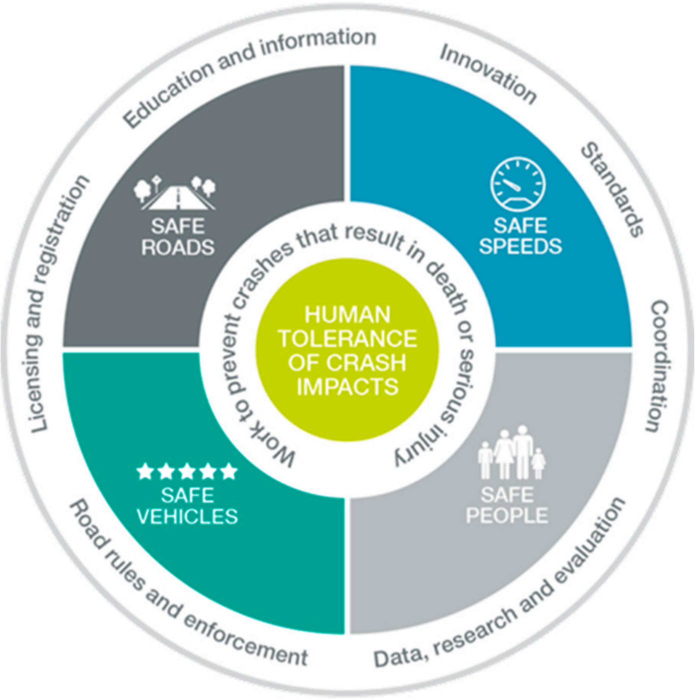

Figure 1. Graphical representation of the Safe System model, from Safer Roads, Safer Queensland: Queensland's Road Safety Strategy 2015–2021 [11], http://roadsafety.gov.au/nrss/safe-system.aspx (accessed on 15 January, 2022). Licensed under: www.creativecommons.org/licenses/by/3.0/au/deed.en (accessed on 15 January 2022).

Traditionally, the four pillars noted above are represented as a circle with four quadrants, with no clear explanation as to how each of these quadrants interacts with, and functions within, the system. It is widely accepted that a fifth pillar now exists, which is referred to as 'emergency response'.

A sharper focus on the role of impact speed in determining the risk of death or severe injury in a crash has been a feature of the introduction of Vision Zero and Safe System. Figure 2 shows a series of fatal risk curves as a function of impact speed for various types of road crashes. According to the curves, a pedestrian impacted at 34 km/h, a driver struck in a side-impact at 50 km/h or a head-on collision at 74 km/h would have a fatality risk of 20% [12,13]. The probability of a fatality as a function of impact speed cannot be considered definitive, as there is a great deal of variation in the combinations of impacts that can occur between various types of road users. However, the curves shown in Figure 2 are broadly indicative of how risk is affected by impact speed. They suggest a rapid rise in probability for each crash type, as impact speeds exceed the values that coincide with an approximate 10% probability of a fatality.

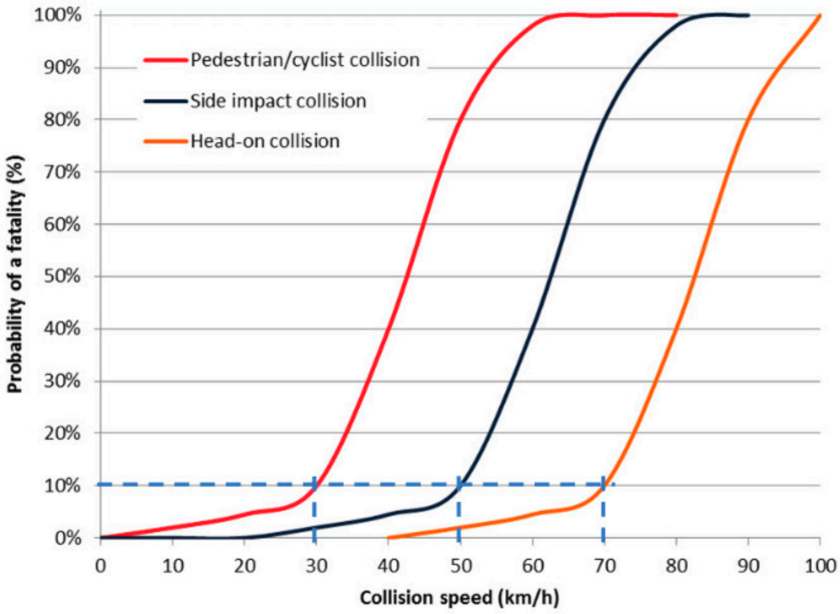

Figure 2. Relationship between crash speed and probability of a fatality, based on Wramborg (2005) [12] and Jurewicz et al. (2015) [13] [from Road Safety on Four Continents 2005 Conference and Elsevier journal, https://www.sciencedirect.com/science/article/pii/S2352146516304021 (accessed on 17 February 2022)] © 2016 The Authors. Published under the CC BY-NC-ND license.

2. Safe System Design

On 18 August 2020, the United Nations General Assembly proclaimed 2021–2030 as the Second Decade of Action for Road Safety, setting a goal of reducing road traffic deaths and injuries by at least 50 percent from 2021 to 2030 [5]. The UN also resolved to encourage the application of Safe System principles across all areas, especially in the design and operation of roads. The UN resolution related to the application of Safe System design principles built specifically upon Recommendation 5 of the Academic Expert Group (AEG), which was formed to advise the 3rd Global Ministerial Conference on Road Safety. The theme of the conference was Achieving Global Goals 2030 [5,7].

Recommendation 5 states, “In order to realize the benefits that roads designed according to the Safe System approach will bring to a broad range of Sustainable Development Goals as quickly and thoroughly as possible, we recommend that governments and all road authorities allocate sufficient resources to upgrade existing road infrastructure to incorporate Safe System principles as soon as feasible”.

This paper provides several examples of how the application of the Safe System design principles is likely to greatly enhance safety outcomes and professional culture, as well as contributing to the Sustainable Development Goals.

2.1. Key Categories of Systemic Risk

Many jurisdictions around the world are adopting the UN-supported global goal of halving road deaths and serious injuries by 2030, aspiring to the longer-term vision of eliminating severe road trauma by 2050 [1,5]. To achieve these near- and longer-term goals, it is essential for road authorities to focus investment on the major types of crashes that characterize severe road trauma. Crashes which produce severe injury or death can be distilled to a manageable number of categories [10]. Attempting to find unique solutions to individual crashes blinds us to the recurring features which define only a limited number of high severity crash types. This gives rise to the notion of systemic risk producing systemic crash types [10,14].

Systemic crash types may vary according to the road design features, the types of road users and the travel speeds of vehicles. Despite these variations, systemic crash types typically fall into a finite number of broad categories, as shown in Table 1 below.

Table 1. Annual average fatal and serious injury crashes by frequency and percentage in Victoria, Australia (Transport for Victoria, 2019).

Crash Type	**Description**	**Annual Average**	
		Number	**Percent**
High-speed lane departure	High-speed departures of vehicles from their lanes, leading to head-on collisions, collisions with hazards in the roadside or vehicle roll-overs	673	13
Vehicle–vehicle at intersections	Vehicle-to-vehicle collisions at intersections, including side-impacts and turning maneuvers across the path of approaching vehicles	585	11
Rear-end	Rear-end collisions (at intersections and between intersections)	650	13
Pedestrian impacts	Pedestrians struck by vehicles when crossing between intersections or at intersections, especially when vehicles are turning	588	11
Bicyclist impacts	Bicyclists struck by vehicles when riding between intersections or negotiating intersections, especially when other vehicles are turning	398	8
Motorcyclist impacts	Motorcyclists and other powered two-wheelers struck by vehicles when riding between intersections or negotiating intersections, especially when other vehicles are turning	854	17

Note: Percentages should not sum to 100.

While multiple crash types not mentioned in Table 1 occur in significant numbers globally, and should not be ignored, the above crash types dominate the challenges typically faced in many parts of the world. Historically, preventing these crashes has involved a strong focus on preventing the driver and/or other road user errors that lead to the crashes [14]. While this approach has yielded substantial improvements in the safety of motorized travel, continued heavy reliance on this thinking is likely to limit progress toward achieving the ambitious road safety targets. Instead, greater attention must now be directed to the combined effects of all pillars intrinsic to a safe road transport system, including an increased emphasis on the design and operation of vehicles and of roads, and the matching of travel speeds in a way that forgives foreseeable human error. These propositions are explored in greater detail for three of the major high-severity crash types listed in Table 1 above, as a means of illustrating how system-based design can produce much greater improvements in safety than has been possible, historically. These include fatal and serious injury crashes from (i) high-speed lane departure crashes, (ii) vehicle-to-vehicle intersection crashes, and (iii) crashes involving collisions with pedestrians.

2.1.1. High-Speed Lane Departure Crashes

Unintentional lane departures often occur at high speeds and frequently result in fatal or serious injury collisions with roadside hazards or with oncoming vehicles, also travelling at high speeds. Drivers depart their lanes for myriad reasons, often related to inattention, distraction, drowsiness or impairment [15,16]. Decades of efforts by researchers and practitioners have demonstrated that while the incidence of these human failings can be reduced, they cannot be eliminated. As a consequence, lane departure crashes have been addressed systematically through regulation, education, enforcement or otherwise, by encouraging road users to drive more safely. Attempts to reduce this crash type have also included the following [17,18]:

- Providing better definition of roadways via the use of white guideposts along the roadside, reflective signing and markers to delineate curves;

- Providing better definition of traffic lanes (e.g., provision of painted center-lines and edge-lines complemented with tactile and audible features);
- Realignment of short-radius curves and/or curves with adverse superelevation;
- Creating clear zones so that drivers who leave the road at high speed have approximately 10 m of lateral distance to regain vehicle control;
- Sealing the shoulders of roads so that drivers are provided with adequate space to regain control if/when lane departure occurs.

While the evidence on the effectiveness of these road design features shows that safety can be improved, the magnitude of improvement is incremental, with reductions in injury-producing crashes ranging from 10% to 30% for the above treatment types [18]. Consequently, Safe System principles require drivers and riders to be always travelling at speeds that will not produce severe injury or death (to themselves or other road users) [16]. The consequence of persisting with the conventional approach to addressing key road safety problems is that a substantial residual risk remains after treatment, of the order of 70–90% in this example. This is ethically unacceptable from a Safe System perspective and prevents jurisdictions from achieving their 2030 and 2050 road safety targets [6,7].

Safe System principles acknowledge that human errors which result in lane departure crashes are inevitable and that the specific timing and locations are essentially unpredictable. Given that it is impractical to prepare for where and when such errors will occur in the future, Safe System requires that roads and roadsides be consistently designed to expect and be forgiving of human fallibility. That is, errors, deliberate or otherwise, will continue to occur, and accommodating their consequences must be explicitly built into the processes of designing and operating the physical components of the system. These processes require an understanding of how road infrastructure interacts with vehicles and other road users, and the speeds at which road users move [15,18]. This means that all elements of the road infrastructure must be designed to accommodate the kinetic energy generated by vehicle impacts when they occur at the set speed limits.

The most complete solution to this problem involves the installation of continuous lengths of flexible mid- and side-barriers to manage the kinetic energy of the errant vehicle before it can reach the opposing lane or enter the roadside at high speed [19]. In comparison with the incremental treatments described above, continuous flexible barriers are approximately three times more effective at preventing severe injuries or death, leading to a residual risk of severe outcomes of around 10–15 percent. As selected vehicle technologies, such as autonomous emergency braking (AEB), lane keep assist (LKA), intelligent speed assist (ISA) and active cruise control (ACC) gradually permeate the world's vehicle fleets [20], the residual risks of severe injury due to high-speed lane departures are likely to reduce further. Thus, the combination of Safe System-aligned infrastructure, with advanced in-vehicle driver support technologies, offers a realistic means of ultimately achieving the target of near-zero deaths and serious injuries within the next three decades.

However, there are vast lengths of roads where high speeds are currently both legal and desired by drivers, but where Safe System-compliant infrastructure investments are unlikely to be affordable in the foreseeable future. On such roads, a different approach to the safe management of the kinetic energy of vehicles will be needed. Notwithstanding advanced driver support systems being likely to be beneficial on these roads, such technologies are highly reliant on visible roadway delineation and paved surfaces to perform optimally [21]. Much of the world's high-speed road network does not meet these requirements so will continue to present unacceptable risks while operating at high speed. The only viable means of eliminating severe road trauma on these roads will be to reduce travel speeds, except where it can be demonstrated that it is safe to drive at higher speeds. While such a change in system operation may be unpopular with some parts of society, lower travel speeds not only reduce road trauma but also reduce vehicle emissions, including greenhouse gases, and, so, make a worthy contribution to the sustainability of our planet [17].

2.1.2. Vehicle–Vehicle Intersection Crashes

The very nature of intersections concentrates vehicle-to-vehicle conflicts within a myriad of distinct, spatially scattered spaces, each small relative to the scale of the total road network. Intersections are needed to enable journeys to progress beyond those roads that cross a motorist's path or so that motorists can join traffic on the intersecting road, by turning either left or right. Despite intersections being essential to the effective functioning of the road transport system, they are the source of many severe road crashes, including those that cause death [9].

In their earliest form, intersections were typically four-way cross-roads or three-way junctions that met at a right angle, or occasionally at an oblique angle. They operated successfully and safely while traffic, including horse-drawn vehicles, was light and travelled at low speed because drivers could find safe gaps among the approaching vehicles. If mistakes were made, the low speeds ensured that injuries were rare. However, once vehicle speeds and numbers began to increase, it became necessary to bring order and rules to control the growing numbers of conflicts between vehicles and with the vulnerable road users also using intersections. Signs and signals became the means for bringing order to the functioning of intersections. While these engineering measures have improved the overall functionality of intersections over the decades, especially in terms of the efficient flow of traffic, they have generally been inadequate in preventing crashes and consequent severe injuries. Fundamental improvements in safety at intersections are long overdue. Today, the most problematic crash types at intersections [22] involve the following:

- Side-impacts by one vehicle into another—in these circumstances, the side structure of the struck vehicle offers minimal protection to its occupants;
- Pedestrians, cyclists or motorcyclists (unprotected road users) struck by vehicles in a range of configurations, often involving turning traffic and/or failure of the driver to give way—unprotected road users have low thresholds to severe injury compared with vehicle occupants;
- Vehicles turning across the path of an approaching vehicle, resulting in head-on or angled collisions with the front of one or both vehicles—in this scenario, impact speeds are often high and impact angles unfavorable due to a strong lateral component of impact forces;
- Rear-end collisions, where high speed and/or mass differentials are involved, such as at traffic signals.

The main reason these crashes are problematic is that, even at legal speeds, the crash energy often exceeds the capability of vehicle structures to adequately protect their occupants. In the case of unprotected road users, corresponding impact speeds result in higher chances of severe injuries, even death. Regrettably, these safety outcomes at conventional intersections have been common and accepted for decades. They can be said to be systemic in nature for intersections.

To reduce the incidence of this systemic source of severe injury, previous efforts tended to focus on reducing the risks of crashes from occurring. Little or no consideration was given to opportunities to prevent exchanges of crash energies from exceeding levels that are safe for humans, that is, ensuring crash energies do not exceed the biomechanical limits of humans. When the focus shifts to accepting that humans perform imperfectly on roads and that mistakes will be made—often foreseeable mistakes—and that kinetic energy must be managed to safe levels, new solutions begin to emerge.

Traffic signals have been designed to promote safe and efficient traffic flow, yet the flow of traffic is regularly interrupted by a red signal, which requires motorists to stop while intersecting traffic moves through the intersection. This sets up the conditions for pedestrian, rear-end, turn against oncoming traffic and side-impact crash types, as well as a variety of other, less prominent impact configurations. Traffic regulations have been carefully written and rewritten over time to prevent such events, and traffic signals have been designed and redesigned to address the recurring safety problems. Turn arrows have been added, mast arms installed, flashing warning signals included, traffic lanes redesigned, signal timings fine-tuned, and signal phases reconfigured, as well as an array of other 'band-aids' applied to a fundamentally unsafe intersection design form. Traffic signals have proven to be unsafe because they allow the exchange of intolerable crash energies when inevitable human errors occur. The same can be said of intersections controlled by stop and give way/yield signs.

In some countries, roundabouts are commonly used, with great success for many decades, to regulate traffic at intersections [23,24]. A well-designed roundabout will not only prevent crashes, but will ensure that when crashes do occur, the exchange of energy between colliding vehicles lies below the thresholds of severe injury. Roundabouts perform at low risk because they constrain the combination of speed and conflict angle between vehicles on intersecting trajectories to inherently safe levels. In urban settings or where unprotected road users can reasonably be expected, additional care is needed in designing to explicitly achieve speeds lying within tolerable limits for road users who do not have the protection of a vehicle structure around them. In The Netherlands, safety platforms have been installed in advance of signal stop lines to help protect cyclists and pedestrians. In Australian trials, safety platforms have reduced travel speeds substantially, by around 15 km/h [25].

This comparison between the design, use and safety performance of conventional traffic signals and roundabouts illustrates the differences in safety outcomes that result from applying the philosophy and principles of Safe System. Increasingly, alternative intersection design forms, based on managing kinetic energy transfer in crashes to safe levels, are being developed and trialed in various parts of the world where Safe System thinking is being applied in practice.

2.1.3. Pedestrian Crashes

For a wide range of reasons, including the sustainability and livability of our cities and towns, the benefits of active travel are increasingly being recognized and promoted. The health and environmental benefits of walking and cycling are also strong drivers of a shift to active travel, which is expected to lead to reduced traffic congestion, as well reducing traffic noise and air pollution in cities and towns. However, more walking and cycling means greater exposure of unprotected road users to the risks posed by vehicular traffic. The World Resources Institute [26] noted a 4% increase in pedestrian deaths in the U.S.A. between 2017 and 2018, while cycling deaths increased by 3.7% per year over the 10-year period up to 2019. Similar figures were published by the National Safety Council [27]. These figures were not adjusted for increases in pedestrian or cycling movements.

Due to their intrinsic vulnerability, it is clear that those who walk and cycle are at heightened risk of death or injury when involved in traffic crashes. More needs to be done to protect such vulnerable road users, not only for their own safety, but also to support the wider goals of population health and well-being, environment and climate change, urban livability, social equity and connection, and a host of sustainability benefits [26].

As indicated in Figure 2, not surprisingly, pedestrians (and cyclists) have much higher chances of dying in a crash, at a given impact speed, than vehicle occupants. While the research represented in Figure 2 cannot be regarded as absolute or definitive, many road safety experts believe it to be strongly indicative of the risk relationships that exist in various systemic crash types. While it is not possible to state with precision that there is a 10% chance of death to a pedestrian struck at 30 km/h (as indicated in Figure 2), practical experience tells us that too many pedestrians die when struck at 30 km/h and those who survive invariably sustain serious, often life-changing, injuries. From this perspective, impacts at 30 km/h remain unacceptable within the Safe System context, despite the absence of a robust mathematical relationship between impact speed and the risk of death to a struck pedestrian. Vehicular travel speeds of 30 km/h have been adopted as representing the safe threshold for pedestrians in areas of mixed traffic [28].

A key recommendation of the Academic Expert Group, formed to advise the 3rd Global Ministerial Conference on Road Safety, held in Stockholm in February 2020, stated, "In order to protect vulnerable road users and achieve sustainability goals addressing livable cities, health and security, we recommend that a maximum road travel speed limit of 30 km/h be mandated in urban areas unless strong evidence exists that higher speeds are safe". This recommendation has since been incorporated into the United Nations Global Plan for the Decade of Action for Road Safety 2021–2030 [29]. Subsequently, the Global Plan states, "In densely populated urban areas, there is strong evidence that even the best road and vehicle design features are unable to adequately guarantee the safety of all road users when speeds are above the known safe level of 30 km/h." [29]. Therefore, drawing upon the guidance of world experts in road safety, there is a pressing need to shift from a design philosophy that seeks primarily to prevent crashes, to one that also seeks to manage the kinetic energy of vehicles to inherently safe levels. This corresponds to designing to permit travel speeds only up to 30 km/h in densely populated areas [28], in the knowledge that drivers and pedestrians are prone to make errors and to experience performance lapses, and when such events occur, no individual should be killed or seriously injured.

A shift in design philosophy means that pedestrians cannot be expected to choose safe gaps in high-speed traffic along busy urban roads. Even with the addition of signals, zebra crossings or other devices to assist pedestrians, safety relies on drivers giving way when a pedestrian begins to cross and on pedestrians crossing according to the regulations for the use of crossings. Many decades of experience shows that drivers do not always give way when required by law, and pedestrians do not always comply with the laws for using crossings. Non-compliances lead to system failures, often at legal speeds that result in death or severe injury to the pedestrian. A strong first step in addressing these contributions to pedestrian crashes and to the serious injuries that result would be to reduce area-wide speed limits to 30 km/h where pedestrians can be expected or need to cross. Over time, drivers will adapt to the new limits and, where necessary, specific areas and locations may need traffic-calming infrastructure to secure speeds to safe levels.

As vehicle fleets mature, it is inevitable that proven advanced driver assistance system (ADAS) safety technologies, such as AEB and forward control assist (FCA) will penetrate fleets, and fewer crashes will occur at 30 km/h because of the ability of these technologies to moderate vehicle speeds. Consequently, crash forces will be minimized, and critical kinetic energy levels prior to any impact with a pedestrian or other unprotected road user will also be reduced. Other technologies, such as intelligent speed assistance (ISA), improved energy-absorbing properties of vehicle fronts, automated enforcement of travel speeds and geo-fencing of vehicles will help to reduce the size of the residual risk of severe injury that remains after 30 km/h speed limits are introduced.

Thus, system-based design, in which the capabilities and limitations of humans and vehicles, the energy given to vehicles due to speed limits and the role of infrastructure are explicitly considered, can reduce risk of pedestrian deaths from traditional values of around 10–20% to around 80–90%. Residual risk will be further diminished as vehicle technology matures and permeates fleets. The simple achievement of reducing urban travel speeds from 50 to 30 km/h can reduce the risk of fatalities by around 90% [30]. Reductions in risk will grow as proven driver support systems gain hold in vehicle markets.

2.2. Summary

Despite the uniqueness of individual crashes, they share many common features and, as such, can be grouped into a relatively small number of categories that can be regarded as systemic for particular combinations of road type, speed limit and setting. When Safe System principles, particularly those concerning the safe management of kinetic energy when foreseeable forms of human errors and performance lapse occur, are applied to road design, the residual risk of severe injuries or deaths can be reduced by an order of magnitude. This compares with traditional approaches to treating the same systemic crash types with measures based primarily on reducing crash risk; these measures tend to yield reductions in deaths and serious injuries in the order of 20–30%, or a halving at best [31].

This paper explored three key systemic crash types which occur globally:

- High-speed lane-departure crashes;
- Side-impact crashes at intersections;
- Pedestrian impacts.

By comparing conventional treatments of the above crash types with Safe System-compliant solutions, vastly improved safety outcomes can be delivered and sustained. There is a strong likelihood that the growing preponderance of advanced vehicle safety technologies will help further reduce the residual risks of serious trauma. However, for some road types and settings, lower speed limits will be necessary to ensure vehicle safety features can function optimally, particularly where low road design standards preclude low risk travel at current speed limits. In terms of sustainability, Safe System designs which result in lower travel speeds will reduce air pollution and fuel use, thereby contributing to a more sustainable future. In cities and towns, less air and noise pollution resulting from lower travel speeds will support high-level sustainability goals.

3. Discussion

3.1. Exposure to Latent Risk

Inadequate infrastructure design exposes communities to the ever-present latent risk of avoidable death or severe injury until Safe System conditions can be delivered. The aggregate effect of under-investment in safety imposes on communities high levels of loss of life and long-term health, leading to sustained high economic impacts. Ironically, the impacts of poor road design are overtly visible in terms of health outcomes, while the long-term consequences of such designs fade from notice [26].

3.2. The Distribution of Impacts

The negative impacts of road trauma are not evenly distributed across societies. Specific community groups suffer more than others, with those suffering most often belonging to groups that are already among the most vulnerable or disadvantaged in society [32]. For example, individuals who cannot afford to own a vehicle are obligated to use public transport, walk or cycle as means of transport. While these are the more sustainable transport modes, they expose these road user groups to heightened risks when they mix with vehicular traffic travelling at high speeds on roads where motorized traffic is given priority.

It is also well recognized that low-income individuals and families that own cars are generally restricted to vehicles that are older and less safe, leaving these already disadvantaged people exposed to greater risks.

3.3. Support for the Sustainable Modes of Travel

The world is struggling to find critically needed solutions to the problems of global warming and climate change. It is imperative that the road transport sector is considered part of the global solution to these problems [33]. A reduced reliance on private car travel and a shift to active, sustainable modes of travel are needed if we are to reduce greenhouse gas emissions from road transport.

Active travel must be supported and encouraged, not only for the health of individuals and communities, but to diminish our reliance on the use of cars. Active travel is naturally sustainable. At present, it is inevitable that car owners will be reluctant to shift to public transport, walking or cycling because of personal inconvenience and/or the risks they would face on high-speed and high-volume roads [33]. As an example, consider families with school-aged children. The limited amount of public transport and dedicated footpaths or cycling paths at present restricts the ability of parents to allow their children to travel to school independently. As a result, parents are obligated to drive their child(ren) to school. Consequently, large numbers of vehicles converge on schools during start and end periods, causing traffic congestion, even greater safety problems, and increasing noise and air pollution. This further diminishes the willingness of families to allow their children to go to and from school by active and sustainable modes. A vicious cycle is created [34].

To address this issue, large-scale programs that deliver infrastructure, designed to meet Safe System principles, are needed. Furthermore, the travel speeds of vehicles that interact with children and their families on school-related journeys must be secured to 30 km/h or lower, to ensure the safety of children walking or cycling to school. One of the recommendations of the Academic Expert Group [7] is that "In order to protect vulnerable road users and achieve sustainability goals addressing livable cities, health and security, we recommend that a maximum road travel speed limit of 30 km/h be mandated in urban areas unless strong evidence exists that higher speeds are safe". The City of Oslo recorded no pedestrian or cyclist deaths for the entire year of 2019 (and only one road death, involving a vehicle occupant) [35]. Travel speeds have been progressively reduced in Oslo through combinations of lower speed limits and traffic-calming infrastructure, in accordance with the principles that define Safe System.

The potential for achieving safe travel speeds, not exceeding 30 km/h, presents a major opportunity to deliver safe conditions, not only for children and families on school journeys, but for the wider community. Conditions which are safe for pedestrians and cyclists are invariably safe for vehicle occupants.

3.4. *The Added Costs of Retro-Fitting Safety*

Road designers have two main options when considering the form of design for any future project. From a safety viewpoint, it is ethical and, therefore, always preferable to adopt Safe System principles so that the residual risk of severe crashes is minimized, as far as is practicable, given today's knowledge of best practice design. By achieving this state of minimum practical risk at the earliest possible time, thousands and potentially millions of road users who will pass through the completed project will avoid the risks imposed by unsafe infrastructure for decades ahead. While Safe System-aligned design may initially be more costly than traditional design choices, designing for Safe System performance may be of lower total cost to society over the long term [36]. The traditional approach of investing in incremental safety improvements, which may not ultimately form part of the final Safe System-aligned design, can result in higher overall and ongoing costs that need to be borne by society to reach the ultimate design form, in multiple stages. Additionally, communities will need to pay for the avoidable trauma sustained over the intervening period, which often builds to decades. These costs are not only monetary in nature, but are indirect costs that result in human burden. Attempting to correct safety deficiencies built in at the outset can also be more costly, often because the initial design precludes options that would otherwise form part of the ultimate Safe System end-state.

Both ethically and financially, Safe System design from the outset should be the default position and only compromised by exception.

3.5. *Professional Responsibilities*

Road designers and system operators exhibit a high level of professionalism in their work. Because there are still relatively few tools available to the profession to quantify the safety consequences of design decisions, and so support the transition to Safe System-aligned design, there continues to be heavy reliance on design standards that have not been comprehensively updated to meet Safe System principles. Many of the existing standards and tools were developed decades ago, with an underpinning philosophy of balancing mobility and safety. As a result, unacceptable levels of risk have been experienced by individual road users in pursuit of fast and efficient movement of vehicles. The risks of severe trauma will continue to be built into future road projects, until a fundamental shift in thinking takes place. We now understand much more clearly that it is not acceptable to make design and operational decisions, in the interests of greater mobility, knowing that this leads to higher levels of avoidable road trauma. Based on today's knowledge and translation of Safe System into practice, much safer road use is achievable today [37].

It is well accepted that road designers and system operators have a professional duty of care to design to keep road users safe [38]. Unlike the road design and system operation professions, road users themselves are not well informed about the true risks they face when using the road transport system. Most road users can only draw on very limited experiences—usually their own or, perhaps, those of a small number of others with whom they are somehow acquainted. They are, therefore, subject to optimism bias because of the narrow perspectives and limited insights that they can bring to decisions about safe road use. This results in today's road users believing that the risks faced in using the system are minimal, which for any one individual is essentially true. However, it also means that judgements about the risks associated with travel speed tend to be under-estimated and thought of as mainly affecting crash risk. Given that many people believe they are 'above-average drivers' [39], they trust the guidance given by speed limits when setting their own travel speeds. However, it is well established that crashes often happen at the travel speed (that is, with no braking occurring prior to impact) and that impacts at the speed limit will frequently lead to death or severe injury. More specifically, road designers and system operators have a duty of care to all road users to accommodate the incomplete knowledge and optimism bias characterizing many drivers and riders. When hundreds of thousands, even millions, of road users, holding this belief use the system every year, the system-wide effect on trauma is substantial.

One of the major premises of the Safe System is that "designers, builders and users of the road transport system have a responsible and moral obligation to anticipate human fallibility and prevent or minimize the injury which can occur as a result of human error and/or poor design" [38]. Given that road users are typically not well informed about how to use the road transport system safely, especially with respect to what can happen when errors are made, even at legal speeds, system designers, builders and operators have a moral obligation (that is, a professional duty of care) to anticipate and accommodate these inherent shortcomings and fallibilities of road users. Road design engineers and operators are uniquely placed to understand and address these critical issues through their choices in design, construction and operation.

To neglect or overlook this professional duty of care has the potential to harm the moral culture of the profession.

3.6. The Role of Political Leadership

In moving from principles to practice, the critical role of politicians and senior leaders in road agencies in ensuring the delivery of safe mobility by applying the principles of the Safe System cannot be overstated. For decades, high-order leadership and commitment have been, and continue to be, needed at the highest levels of government to drive the changes required within road agencies to move from the status quo to practices founded on ethics, the inevitability of human error and designing a forgiving road transport system. This need for leadership has been brought into sharp focus in recent years through the United Nations' and World Health Organizations' efforts to engage government ministers in Global Ministerial Conferences on Road Safety [7]. Among the numerous valuable contributions from government ministers from around the world to the Third Global Ministerial Conference on Road Safety, held in Stockholm 2020, was the leadership shown by Sweden's Mr. Tomas Eneroth, Minister for Infrastructure, Ministry of Infrastructure, Sweden. The Minister's leadership and commitment reflects the national government's long-term commitment, first made in the Swedish Parliament in 1997 [40], to realizing the Vision Zero goal of eliminating severe trauma from its roads. While politicians and agency leaders can support large-scale investment in Safe System-aligned infrastructure, they will also need to lead on introducing safe travel speeds. Politically, speed corrections can be controversial, but are both essential and highly affordable. Moreover, adjustments to travel speeds will commonly support the UN Sustainable Development Goals, for example, reducing emissions, helping to meet climate change targets, supporting healthy, active travel and delivering a host of non-safety benefits for society.

4. Conclusions

Safe System thinking encourages us to accept that road users are fallible and will not perform flawlessly for the entire time they are using the traffic system. As a result, designing a Safe System-compliant transport system is highly likely to minimize the road trauma currently being observed, and bring significant road safety and environmental gains.

One of the inferences from the UN Resolution of August 2020 is that much of today's road design practices produce infrastructure that is unsafe, given the speeds at which motorists are invited to travel and their propensity to occasionally fail. The recognition of this fact underpins the recommendation of the AEG that states, "*In order to realize the benefits that roads designed according to the Safe System approach will bring to a broad range of Sustainable Development Goals as quickly and thoroughly as possible, we recommend that governments and all road authorities allocate sufficient resources to upgrade existing road infrastructure to incorporate Safe System principles as soon as feasible*". When we fail to design according to Safe System principles, we invariably, inadvertently, incorporate a sizeable residual risk of death or severe injury along a road or at an intersection, that will remain in place until some future time when the next opportunity for modifications happens to present itself. When a road user experiences a lapse in performance in such circumstances, the permitted travel speeds often result in high-energy collisions, where the energy exchange during the collision exceeds the tolerance of the human(s) involved in the crash. Only when the energy exchange remains within safe limits can we be satisfied that Safe System principles have been successfully applied. When individual components of roads—intersections and links between intersections—are not designed to meet Safe System principles, the aggregation of all the individual residual risks is substantial and helps explain why jurisdictions suffer from unacceptable levels of injury and death on their roads.

Today, road designers and system operators have far greater knowledge and insight on matters related to safety than did past generations of their profession. For most jurisdictions, Vision Zero and the Safe System emerged between 15 and 25 years ago, so a considerable period has been available to align practices with Safe System imperatives. Notwithstanding, sub-optimal decisions on safe design continue to be made, leading to the recent call by the United Nations, as part of the Second Decade of Global Action on Road Safety (2021–2030) to adopt Safe System design principles. Apart from the permanent and extensive sustained impacts on human life and health and on national economies, there is potential to inflict long-term harm on the culture of road-based professions. As the best global guidance and expert advice on road design and system operation were provided in 2020 and reinforced in 2021, continued reliance on outdated design and construction practices, which produce inherently unsafe infrastructure, will undermine the moral standing of the profession. We would not accept such an approach from medical professionals in caring for our health or epidemiologists in protecting communities from global pandemics. It is vital that the standing and culture of the road design and system operation professions strive for the highest standards of safety (and environmental responsibility), and that compromises to achieve economic or other advantages are non-negotiable for all new roads and when redesigning existing roads. Long-term harm to the culture of the professions must be avoided, as its rectification can be difficult and take many years.

Not designing according to Safe System principles has numerous substantial effects, some of which are difficult to quantify but can, of course, be far-reaching. Given the rate of growth of road transport systems globally, it is timely that Safe System principles are re-visited by road authorities and brought to the forefront of road engineering and design practices. To drive the necessary changes at scale, however, sustained high-order leadership and commitment will be essential from politicians and the heads of road agencies.

Author Contributions: Conceptualization, B.C. and S.P.; data curation, S.M.; writing—original draft preparation, B.C. and S.P.; writing—B.C. and S.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented within the manuscript was obtained directly from the relevant road authority as cited, and are not publically available.

Conflicts of Interest: The authors declare no conflict of interest.

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