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The Safe Systems Pyramid: A new framework for traffic safety

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ABSTRACT

Introduction: Civil engineers play an outsize role in shaping the built environment, which plays an outsize role in health, especially in transportation safety. While there is growing interest in integrating public health and transportation engineering and planning to improve safety outcomes, existing efforts fall short.
Method: We review prior efforts to integrate public health into transportation safety, and frameworks from injury prevention and control and risk management.
Result: Based on the Hierarchy of Controls and the Health Impact Pyramid, we present a framework for prioritizing policies and interventions, known as the Safe Systems Pyramid, that contains five ascending levels – Socioeconomic Factors, Built Environment, Latent Safety Measures, Active Measures, and Education. The levels of the framework prioritize increased population health impact and decreased individual effort.
Conclusions: Frameworks like "The 3 E's" emphasize collaboration rather than a change in thinking and action among transportation safety professionals, and do not prioritize specific actions. We argue that Vision Zero and other "Safe Systems" prioritize implementation of policies, programs, and infrastructure to increase population health impact by considering the individual effort necessary to obtain a protective effect.
Practical applications: This framework is designed to shift the thinking of engineers, planners, and policy makers that shape the transportation system. We conclude this work by applying the Safe Systems Pyramid to a hypothetical Vision Zero program, highlighting how the framework can be used to prioritize efforts using a Safe Systems approach.

Introduction

The transportation system influences health outcomes in many ways, from safety to mental health to air quality (Glazener et al., 2021). For public health professionals, the transportation sector influences mental health and wellbeing, one's opportunities to be physically active, access to healthy diets, medical care, and exposure to infectious diseases (Widener & Hatzopoulou, 2016). But the intersection of transportation and health is increasingly of interest to civil engineers, city planners, and public health practitioners. Despite this overlapping interest among fields, few transportation professionals are trained in public health or exposed to the conceptual frameworks that underlie it.

In particular, the injuries and deaths that result from crashes within the transportation system present a significant public health problem, which can be studied with a public health approach. Understanding the nexus of transportation with health and safety outcomes is crucial to solving the complex problem of traffic safety, but there are few efforts to incorporate public health frameworks into transportation practice. In this work, we propose "The Safe Systems Pyramid" as a means of evaluating transportation safety policies and interventions. This framework is based on the science of injury prevention and control and risk management, the foundations of which are already entrenched in public health professionals' approach to injury prevention (Baker & Haddon Jr, 1974). Most research on transportation and public health discusses health outcomes related to the transportation system. Instead, we propose that transportation professionals apply public health principles in their work to *prevent* adverse health outcomes. We believe that, if implemented, the Safe Systems Pyramid will help transportation professionals prioritize projects for safety and communicate their priorities with the public.

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In this work, we first report on the intersection of transportation and health as it is in current research and practice, followed by a brief summary of the evolution of frameworks for traffic crashes and injuries, pointing out the limitations of each approach. We then describe the existing public health frameworks most relevant to our proposed model, pointing out their limitations as applied to the transportation system. We then present our proposed framework for prioritizing traffic safety interventions and policies. After outlining the framework, we explain in detail each level of the pyramid, naming examples. Finally, we conclude this work with recommendations for future research.

Background: transportation, safety, and public health

Existing integration of transportation and health

The transportation system's influence on health outcomes has been widely studied, from the burden of injuries to its influence on physical activity, mental health, air pollution, and other areas of health (Boarnet et al., 2005; Christofa et al., 2020). Despite this interest in how the transportation system influences health, there has been relatively little attention in how to incorporate principles from the field of public health into transportation practice and research.

There are some notable exceptions. Examples of incorporating public health ideas into engineering practice at the individual level include conducting Health Impact Assessments, incorporating health outcomes into the planning process, gathering data to evaluate transportation policies, and collaborating on transportation projects that promote healthy living or better access to medical care (Boarnet et al., 2005; Dannenberg et al., 2008; McDonald et al., 2014; Meehan & Whitfield, 2017; Whitfield et al., 2017). This work reflects an interest in improving health outcomes by minimizing transportation's negative influences and maximizing the positive ones, but they do not address the systematic safety issues present in engineering practice, nor are they comprehensive in their approach to solving transportation safety problems.

In addition to these individual level efforts to promote health in transportation, there are also several examples at the institutional level to increase collaboration among public health professionals and engineers. For example, the National Highway Traffic Safety Administration (NHTSA) was led initially by a medical doctor who advocated for addressing traffic safety as a public health issue (Baker, 1989; Runyan, 1998). Consumer safety and occupational and public health advocates also played a key role in developing vehicle safety standards and creating legislation on intoxicated driving. These and other programs led to traffic safety being named as one of the major public health achievements of the 20th Century, although the benefits were primarily for motor vehicle occupants (CDC, 1999).

Despite this progress, there are many more ways to integrate public health and transportation engineering thinking, practice, and research – and there is interest in doing so. The American Public Health Association, American Planning Association, and the Institute of Transportation Engineers have all authored reports or sponsored initiatives highlighting transportation and health (Malizia, 2006; Ricklin & Kushner, 2013.; American Public Health Association, n.d.; Institute of Transportation Engineers, n.d.). Several journal articles and reports have outlined the funding and planning processes specific to their profession, the defining terms which differ between fields but have a similar meaning, and a research roadmap for transportation and health (Botchwey et al., 2009; Dannenberg et al., 2021; Steedly et al., 2019). There are also curricula aimed at training students in both transportation and health (Botchwey & Trowbridge, 2011; Pollack et al., 2015).

Communication among siloed professionals is necessary and useful to promote collaboration, and these previous efforts have begun this process. But prior efforts focused on collaboration between fields instead of true integration, which requires new paradigms. Opportunities remain to help transportation professionals working on the built environment understand the methods and practices associated with public health. Our work addresses this need.

The E's framework of traffic safety

To highlight the value of our proposed framework, we compare it with the most frequently cited frameworks in traffic safety today. The "E's" framework– which emphasizes engineering, education, and enforcement is often cited in official planning documents and strategies, such as those from NHTSA, as well as municipal plans (NHTSA 2017; Mendoza et al. 2017; Atlanta Regional Commission 2020). Further, the Towards Zero Deaths National Strategy sponsored by the American Association of State Highway and Transportation Officials, the Governors Highway Safety Association and 6 trade organizations representing transporation safety professionals is based on the E's,and notes it's importance for Strategic Highway Safety Plans, and local Vision Zero plans (National Academies 2022). We believe that this approach to transportation design and planning has limited engineers' and planners' understanding of how their work impacts health and safety.

The E's framework was first proposed by Julien H. Harvey, a transportation planner, in 1923 (Groeger, 2011). The National Safety Council further refined and promoted it, led by its Chief Engineer, Sidney Williams (Damon, 1958). Williams' conception of traffic safety emphasized good public health practice in that he promoted prevention. However, Williams claimed that a "balanced approach" between the three Es would reduce deaths by 50% (Williams, 1935). Further, he emphasized behavioral change above all other interventions, writing "we know that the human factor, the drivers and pedestrians, is more important in causing or averting an accident than either the car or the highway" (Williams, 1935). But ascribing the largest safety hazard to road user behavior and education is at odds with well-demonstrated public health methods of injury prevention, as discussed in the following section.

Despite these issues, the E's framework and the emphasis on human behavior still prevails today. NHTSA, the federal agency dedicated to transportation safety, states that 94% of crashes are the result of human error and includes the E's as its primary framework for thinking about transportation safety in its most recently published strategic plan (National Highway Traffic Safety Administration, 2016). A National Strategy on Highway Safety know as "Towards Zero Deaths" emphasized the 4Es: education, enforcement, engineering, and emergency medical and trauma services (Mendoza et al. 2017). According to the social-ecologic model in public health, however, people operate in a system that presents choices for behavior (Mercy et al., 2007). Similarly, education is not universal and the choices available are not uniform (Nilsen et al., 2008). A public health approach seeks to correct these discrepancies and decrease risk at the population level. Strategies that implicitly or explicitly benefit one population or another are contrary to the goals and objectives of public health.

In the following sections, we further explore how the "E's" of traffic safety fall short by describing public health's injury prevention frameworks of how crashes and injuries occur.

Public health and injury prevention: A brief overview

Injuries as an epidemiologic problem

Energy transfer as the primary cause of injuries

Modern injury prevention and control traces its roots to DeHaven's 1942 analysis of falls from a range of heights (De Haven, 2000). DeHaven, a mechanical engineer and former pilot, believed that airplane and motor vehicle crashes were not the result of random occurrences but could be scientifically studied (Gangloff, 2013).

By studying the medical outcomes, height, and weight of people in 8 cases of falls, DeHaven calculated the force at which people hit the ground (De Haven, 2000; Gangloff, 2013). DeHaven concluded that the human body could tolerate substantial force if it were dissipated over a larger surface or could be absorbed (Gangloff, 2013). DeHaven's analysis of falls also identified *kinetic energy* as the cause of injury. He proposed that distributing or absorbing this energy could prevent injuries and save lives (Gangloff, 2013). Further, DeHaven's analysis highlighted how peak forces at the point of contact determine the extent of injury. Applied to traffic safety, if a crash occurs, the forces can be dissipated by (1) slowing the acceleration of one or both objects and (2) by dissipating the point of contact over space. Both measures decrease the amount of energy transferred to the human body in a crash and could be used to prevent serious injuries. In application, this led to countermeasures such as seatbelts, airbags, and crumple zones to mitigate the transfer of kinetic energy to the human body.

Other public health professionals also took interest in injury prevention. James Gordon presented to the American Public Health Association in November 1948 on injuries as an epidemiologic problem (Gordon, 1949). In his presentation, Gordon proposed considering injuries within the classic epidemiologic triad, writing: "The causative factors in accidents have been seen to reside in the agent, in the host, and in the environment. The mechanism of accident production is the process by which the three components interact to produce a result, the accident: it is not the cause of the accident" (Gordon, 1949).

The epidemiologic triad – consisting of host, agent, and environment – is one of the most basic of public health models, stating that disease results from the interaction among each component of the triad. All three must be present to cause disease or injury, offering opportunities to prevent disease or injury by intervening to eliminate an element of the triad or the interaction between two. Further, Gordon framed the interaction within the larger social context, well in line with later iterations of the epidemiologic triad, such as social-ecologic model. He notes that beyond the simple interaction between host-agent-environment, "whatever the kind or nature of mass disease or injury, the part exerted by the socioeconomic environment is probably the most neglected of any epidemiologic influence" (Gordon, 1949). This focus on the context of where and how injuries occur was a departure from other efforts which prioritized education and enforcement of individual users. This research thus laid the groundwork for later efforts to approach injury prevention and traffic crashes using a public health approach – notably the work of William Haddon.

Energy as the agent of injury

William Haddon's work in the 1950s and 1960s built on prior research by codifying the host-agent-environment relationship more specifically, noting that the agent in injuries is energy, not the physical object that delivers it (Haddon Jr, 1980). Haddon thus modified Gordon's understanding of the epidemiologic triad for injuries by using DeHaven's theory that the agent is energy (Haddon Jr, 1980). The transfer of energy is necessary to cause injury in the same way that biologic agents are necessary for certain diseases.

In addition to refining the host-agent-environment framework, Haddon developed a tool for practitioners to identify different preventive measures, known as Haddon's Matrix (Haddon Jr, 1980). Haddon's Matrix is a well-known and widely applied tool in injury prevention and control (Runyan, 1998). In addition, Haddon wrote extensively on what he referred to as "active" and "passive" measures, noting that both are necessary (Haddon Jr, 1974). Passive measures are those that require little to no individual effort, while active measures require increasing individual effort (Haddon Jr, 1974). Although Haddon's contribution is clear about how to prioritize interventions based on kinetic energy and applies sound public health science for individual instances of injury, it does not necessitate how those interventions should be codified into current policy.

Legacy of public health in road safety

Public health ideas permeated early vehicle regulation policy. Notably, Haddon influenced safety practice and policy by making substantial contributions to the Federal Motor Vehicle Safety Standards, as the first Administrator of what would later become NHTSA, and as longtime president of the Insurance Institute for Highway Safety (IIHS).

NHTSA's role as vehicle safety regulator has saved thousands of lives through countermeasures that dissipate and absorb energy, such as seat belts, airbags, and roll cages (Kahane, 2015). Further, the approach to vehicle safety policy and regulation typically favors passive rather than active measures as safety tasks, like automated emergency braking. NHTSA has regulated these features into vehicles, and IIHS has consistently tested and promoted them as a nonprofit organization – both of which are excellent examples of sound public health thinking adopted by engineers and policymakers.

Despite the remarkable progress achieved from applying the public health approach to vehicle occupants, road traffic deaths and injuries remain high, and deaths among vulnerable road users have increased in recent years, and dramatically increased among pedestrians (NHTSA, 2020). The United States still experiences far more traffic deaths than other high-income countries when adjusting for both population and vehicle miles traveled (Sauber-Schatz et al., 2016; Yellman, 2022). Despite the emphasis on "safety" in infrastructure design, the designs are not informed by the same public health principles that have proven effective in preventing injury, as in vehicle design. Thus, infrastructure design and planning could benefit from a similarly comprehensive approach.

Safe systems and Vision Zero

Vision Zero is an increasingly popular transportation safety policy in American cities (Kim et al., 2017). Vision Zero is a type of "safe systems" approach to road safety; a collection of strategies and design and planning philosophies that systematically reduce traffic injuries and fatalities by addressing the cause of crashes. Embedded in these strategies and their resulting practices is the assumption that all traffic deaths can be prevented in the long term (Belin et al., 2012; Fleisher et al., 2016; McAndrews, 2013).

Vision Zero plans and policies frequently call for collaboration among transportation and public health agencies and practitioners, where the roles for public health practitioners are typically fundamental public health activities, like data collection and evaluation (Fleisher et al., 2016). However, Vision Zero should be based on the public health philosophies of prevention of risk factors and promotion of protective factors, rather than facilitating collaboration alone (Kim et al., 2017; McAndrews, 2013).

Sweden, the Netherlands, and the United Kingdom began implementing Safe Systems approaches in the late 1990s and early 2000s, and traffic deaths have declined in these countries nearly 5% each year per capita (Hughes et al. 2015). Notably, these international Vision Zero/Safe Systems/Systematic Safety efforts emphasize the traffic safety as a public health problem, emphasizing the release of kinetic energy as the agent responsible for injuries, and develop interventions based on the biomechanical limits of the human body to mitigate the transfer of kinetic energy, and emphasize system designers role in altering the built environment to prevent injuries and death (Corben et al. 2010; Belin et al. 2012; Kristianssen et al. 2018). In fact, many plans specifically cite the work DeHaven and Haddon when describing the origins of their safe systems programs (Belin et al. 2012). Of note, Claes Tingvall, an epidemiologist himself and one of the early Vision Zero champions, framed traffic safety as the interaction between host-agent-environment in one of the early working papers describing Vision Zero in 1997 (Tingvall 1997).

Other countries have adopted the Safe Systems approach and drastically reduced injuries and deaths, while the United States has made little progress in transportation safety in comparison (Yellman, 2022). Notably, these international Vision Zero/Safe Systems efforts emphasize traffic safety as a public health problem, developing interventions based on the biomechanical limits of the human body (Belin et al., 2012). It appears that Safe Systems approaches that use theoretical basis of injury prevention as a foundation have outperformed those that have only encouraged collaboration.

Why is a new framework needed?

The inadequacy of framing safe systems programs around the E's framework is clear. In addition to the less successful safety outcomes than programs in other countries, it is also evidenced by the frequent addition of new E's beyond the traditional engineering, enforcement, and education; new E's include equity, evaluation, emergency services, economics, ergonomics, exposure, enablement, and examination of competence and fitness (Groeger, 2011; Atlanta Regional Commission 2020). *If the initial E's sufficiently described the safety problem, further E's would not be needed.* Simply adding alliterative titles to the initial list does not help prioritize interventions or suggest anything about their effectiveness at the individual or population level. Adding more E's does little more than dilute responsibility and focus.

Further, the E's framework, even with only the initial 3 E's implies a false equivalency between the different factors and interventions. As engineering, enforcement, and education are not equally effective, the E's paradigm neglects the public health principles which stipulate that population level interventions that require less individual effort should be prioritized, and that one need focus on the pathologic agent (in this case, the transfer of energy).

Applying the health Impact Pyramid to transportation safety

Vision Zero and Safe Systems philosophies framed around the E's require a paradigm shift. We argue that the structure of the Health Impact Pyramid, along with the principles outlined by Haddon, be used as the framework for Vision Zero policies (Frieden, 2010). Instead of simply collaborating with public health practitioners, transportation professionals, including engineers, must understand *how to apply public health concepts* in traffic safety. The principles of prevention, a focus on population health, and an understanding of the specific causes of injury will help engineers and planners implement effective safety policies.

The Health Impact Pyramid is a general framework for public health action that prioritizes interventions that have increasing population health impact and decreasing individual effort needed (Frieden, 2010). The five-tier pyramid is shown in Fig. 1 below. The "Hierarchy of Controls" is a similar framework used in occupational health and safety, displayed in Fig. 2 (CDC, n.d.). Unlike Frieden's Health Impact Pyramid, the Hierarchy of Controls is organized by effectiveness, with the most effective strategies at the top, and least effective strategies at the bottom. The Hierarchy of Controls (Fig. 2) features many of Haddon's Strategies (e.g., one could argue that "preventing the marshalling of energy is akin to "Elimination") but simplifies them into 5 categories.

Elements of Frieden's Health Impact Pyramid and the Hierarchy of Controls are useful for analyzing road safety policies and interventions, but each has shortcomings when applied to road safety. First, Frieden's Health Impact Pyramid is intended to analyze population health impact in addition to the effectiveness of any intervention. Frieden notes that: "Interventions at the top tiers are designed to help individuals rather than entire populations, but they could theoretically have a large population impact if universally and effectively applied. In practice, however, even the best programs at the pyramid's higher levels achieve limited public health impact, largely because of their dependence on long- term individual behavior change" (Frieden, 2010).

Many road safety interventions are effective at the individual level and require individual effort to achieve the intended effect. This results in decreasing population health impact. Improving road safety in the aggregate requires prioritizing effectiveness of the intervention itself as well as public health impact. Unlike the E's framework, the Health Impact Pyramid accounts for both effectiveness, effort, and exposure. However, the Health Impact Pyramid also includes factors that are not relevant to road safety such as "Clinical Interventions," which are mostly not useful in preventing or controlling traffic related injuries.

Second, the Hierarchy of Controls has been applied to road safety to codify different interventions and link them to sustainability policy (McLeod & Curtis, 2022). The Hierarchy of Controls includes explicit inclusion of "Engineering Controls" that are critical for road safety. Vehicle and roadway engineering are important facets of a traffic injury prevention and control strategy. However, we argue that vehicle engineering and roadway engineering differ in their application to population health and whether they require individual effort. For example, automated emergency braking is an important strategy for preventing crashes, but it is only useful if vehicles have the technology installed. On the other hand, built environment interventions expose *all* road users in an area where they are implemented and can thus increase safety for a larger population.

There are elements of both the Health Impact Pyramid and the Hierarchy of Controls that are relevant to road safety, but neither framework fully addresses road safety needs. Therefore, we propose a new framework for road safety resultant of combining both models.

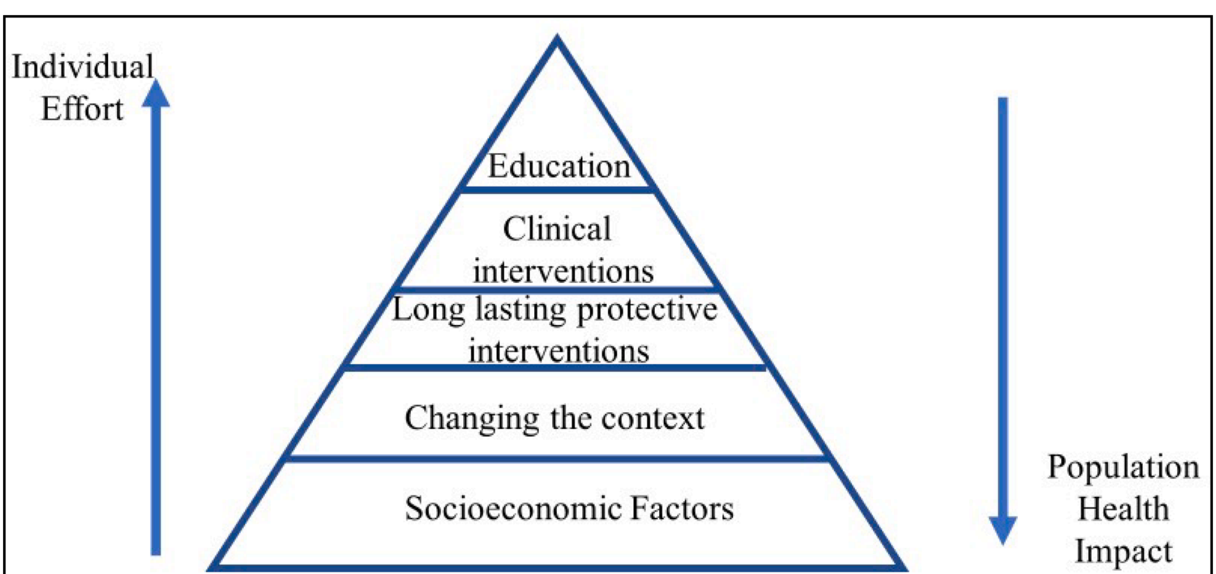

Fig. 1. Health Impact Pyramid (adapted from Frieden 2010).

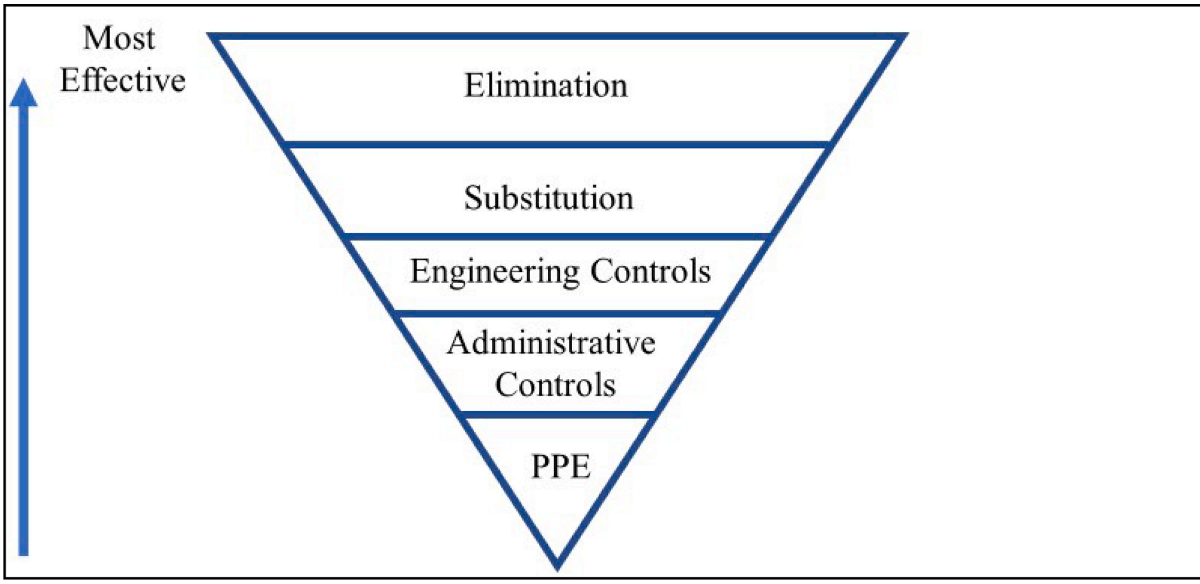

Fig. 2. Hierarchy of Controls (Adapted from the Centers for Disease Control and Prevention n.d.).

The Safe Systems Pyramid

We propose "The Safe Systems Pyramid," shown in Fig. 3. Table 1 describes each level of the pyramid and lists examples of interventions related to each tier. In descending order, the pyramid consists of education, active measures, latent safety measures, the built environment, and socioeconomic factors. In the following sections, we describe each tier of the pyramid.

Uptake, effectiveness, and the size of affected population all influence the population health impact of any intervention or policy. In general, going down the pyramid from education to socioeconomic factors increase the population likely exposed, as elements (and their corresponding policies and programs) that are further down the pyramid requires less individual effort. For example, while education can theoretically reach a large population, it is not universally accessible and requires individuals to understand and apply the concepts they learn correctly to be effective. In contrast, broadly applied built environment measures affect *any* person traveling in that environment. We argue this is more effective at a population level than vehicle-based active and latent safety measures, which are contingent on their prevalence in the vehicle fleet.

The pyramid does not account for the effectiveness of any individual intervention. Thus, engineers and planners must consider the available evidence for any intervention. However, implementing interventions further down the pyramid is likely to increase the size of the population exposed to protective factors, as well as increase uptake. Thus, even if measures at the bottom of the pyramid have a smaller estimated effect size, the effect on overall population health is larger.

Like interventions at the base of the Health Impact Pyramid, interventions at the base of the pyramid that change the built environment and socioeconomic factors often require substantial political will (Frieden, 2010). While the upfront cost may exceed that of interventions at the top of the pyramid, the unit cost per injuries prevention is likely much less than when intervening at the population level.

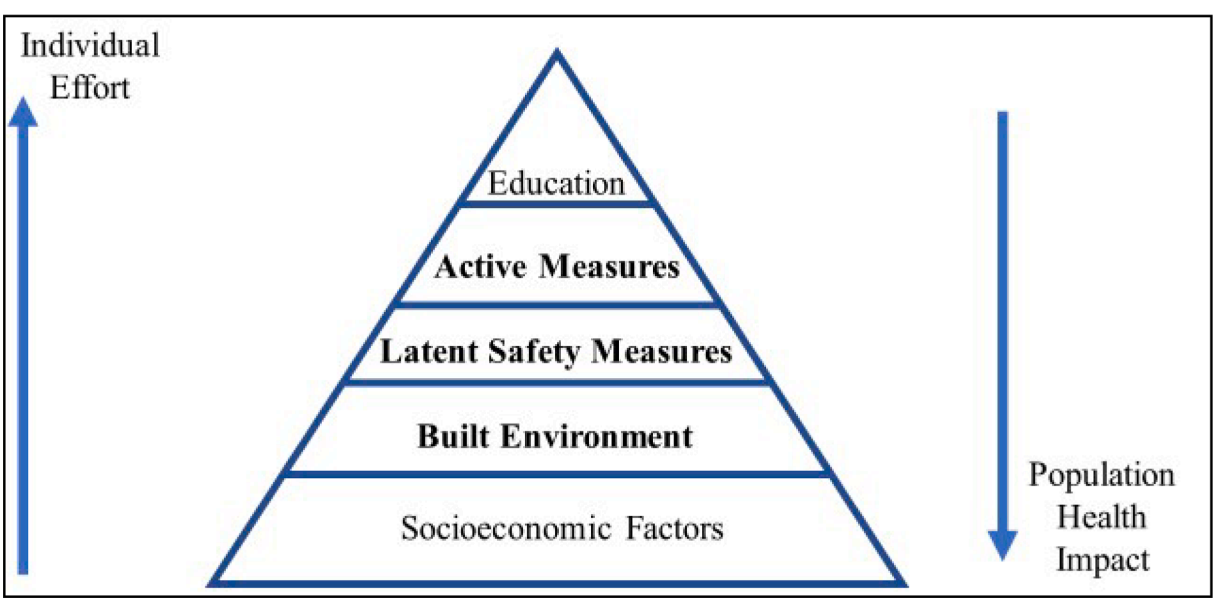

Fig. 3. The Safe Systems Pyramid.

Table 1
Summary table of tiers with intervention examples.

Tier	Approach to prevention	Programs and interventions	Relevant policy
5	Education	Driver education programs; Slow Down Campaigns	Driver's education requirements for licensing
4	Active Safety Measures	Signals and signs indicating that one should stop or yield; forward, rear, and side collision warning; seat belts; helmets	Standards and guidance on where to place signs and signals; vehicle standards requiring safety features
3	Latent Safety Measures	Signal timing that encourages slower traffic progression; leading pedestrian intervals; air bags; automated emergency braking systems; speed governors; alcohol ignition interlocks	Standards and guidance on signal placement and cycle length; vehicle standards requiring the installation of latent safety features
2	Built Environment	Roundabouts; speed humps; chicanes; raised crosswalks; sidewalks; bicycle infrastructure	Design guidance that emphasizes safety over capacity;sidewalk ordinances
1	Socioeconomic factors	Affordable housing near transit; Zoning reform that reduces vehicle miles traveled; Safety features on commercial fleets	Zoning policies; housing policy; occupational safety policy

Socioeconomic factors

In the proposed safety pyramid, we maintain Frieden's approach of listing the socioeconomic determinants of health at the base. Income, education, community safety, social and institutional support (and more) all set context for health outcomes (Frieden, 2010). These factors are the "starting" point for determining many health outcomes, including traffic safety. Rarely, however, are these factors included in traffic safety models; in their review of 121 road safety models, Hughes et al. point out that the social and economic factors are largely excluded (Hughes et al., 2015), which contrasts with public health thinking that the economic context influences decisions and health behaviors (e.g., one's decision to speed or wear a seatbelt is also conditional on the social, cultural, and economic environment).

Importantly, social and economic factors influence one's need to travel in the first place, potentially increasing exposure over time. They also dictate when and where one needs to travel, and under what circumstances. For example, a person who works night shift may travel to work late at night when sight distances are poor and there are more intoxicated drivers on the road. Further, some occupations require people that put themselves at risk on the road. Traffic crashes are the most common cause of occupational death (National Safety Council, n.d.). Truck drivers, delivery drivers, and construction workers regularly put themselves at risk of crashes because their jobs require them to do so.

Similarly, risk of injury is not evenly distributed in space, as low-income people, Black, Hispanic, and Indigenous people are more likely to live near dangerous intersections, higher volume roadways, or on a street that lacks sidewalks (Morency et al., 2012). All of these factors present serious risk to many of people, but as noted above are not typically captured in models. Thus, interventions addressing social determinants of health can help reduce road traffic injuries. The fundamental societal changes required to address these issues go beyond traffic safety policy, but regardless should be viewed as supportive and connected to transportation safety as these factors also influence travel behaviors and culture. However, transportation professionals can incorporate these practices into their work. For example, aligning functional classification with land use and city plans can help create safer, more efficient streets focused on moving people safely (Salt Lake City 2023). Street design decisions can thus prioritize safety, but also mandate that land use do the same. Street typologies in Salt Lake City consider land use context as well as citywide and neighborhood goals, and allocate space based on function with person mobility as the top priority (Salt Lake City, 2023). This can alter socioeconomic conditions traditionally considered outside the purview of transportation professionals to alter the need to travel in the first place.

Built environment

The next level of the Health Impact Pyramid (Tier 2 in Fig. 3 and Table 1) is changing the built environment. The "Built Environment" tier consists of engineering improvements that might be prioritized in the Hierarchy of Controls, but also influences the nature of one's exposure, similar to "Substitution" in the Hierarchy of Controls. For example, if a safer walking environment encourages a walking trip rather than a driving trip, it decreases overall exposure to others on the road.

On a city/town scale, the built environment includes elements such as land use, population density, and access to destinations – all of which influence the distance travelled and mode choice (Stevenson et al., 2016). On the roadway scale, built environment also includes treatments that separate users in space and time using controlled access for high-speed travel, sidewalks and cycle paths for pedestrians and cyclists, and signal phasing. Modifications to the built environment also have a direct influence on the transfer of energy by changing the speed or angle at which vehicles might collide by using treatments such as guard rails, raised crossings, raised intersections, roundabouts, and "centerline hardening" (Chen et al. 2013, Persaud et al. 2001). In addition, compact built environments facilitate less driving at all scales are excellent examples of reducing the amount of force marshalled (via walking or cycling instead of driving), or reducing the time exposed to a higher speed crash (via driving a shorter distance). Compact built environments to reduce driving also support the socioeconomic level of the pyramid, as owning and operating motor vehicles are disproportionately higher for lower income people, and compact built environments can facilitate easier non-automobile travel.

Importantly, changes to the built environment affect the entire speed distribution, rather than eliminating outliers. In-person speeding enforcement is likely to target the fastest drivers, which is akin to only targeting the "sick" individuals rather than the entire population (Richter et al., 2006). Instead, good public health practice shows that the largest population health benefit is in shifting the entire risk curve of the population (Rose, 2001). The population health benefit of shifting all speeds will likely exceed the health benefit of only targeting the highest speeds (Richter et al., 2006).

Although they pose larger up-front costs, may take more time to implement, and require more political will, built environment interventions help reduce risk for traffic injuries systematically. Thus, built environment interventions merit substantial investment for interventions in Vision Zero and other traffic safety programs.

Latent safety measures

In Frieden's initial conception of the Health Impact Pyramid, long-lasting protective interventions include immunizations and colonoscopies. These measures are highly effective but are applied individually rather than to the population, and thus receive less priority for population health impact (Frieden, 2010). Similarly, "Latent Safety Measures" such as airbags and automated emergency braking ("Engineering Controls" in the Hierarchy of Controls) are highly effective and act by decreasing the latent level of risk without requiring human intervention. However, to achieve the maximum population health impact, these measures require a high percentage of individual uptake, and are thus a level below built environment measures that expose a larger population to the intervention.

Many latent measures are focused on vehicle technology. Latent Safety Measures include crash Prevention technologies built into vehicles via design and automation, exteriors that mitigate the transfer of energy to other vehicles and vulnerable road users, automated emergency braking, and lane departure prevention. Notably, many of these technologies are not equally distributed in the vehicle fleet and tend to be available on more expensive vehicle models, and thus only those with the means to purchase them are able to benefit from these safety technologies (Metzger et al. 2020).

Beyond the vehicle itself, other latent safety measures that may be used to alter risk of crashes and injuries. Automated vehicle enforcement via speed cameras, for example, reduces overall vehicle speeds (Wilson et al., 2010). Unlike in-person enforcement, this does not require individual decision making from a police officer to choose who might be ticketed and cited. Further, automated enforcement may help shift the speed curve, rather than target only the worst offenders, increasing population health impact (Richter et al., 2006; Wilson et al., 2010).

Active measures

"Active Measures" are those that are highly effective, act at the individual level, and require a great deal of individual effort. This tier is a combination of elements from the PPE and engineering controls from the Hierarchy of Controls. Active measures such as seat belts, motorcycle and bicycle helmets, and turn signals have been widely deployed in transportation safety. The effectiveness of these interventions is high, and has prevented many injuries, but their health benefit is contingent on individual users (Cummings et al., 2003; Evans & Frick, 1988; Liu et al., 2008). Other active safety measures are available such as forward, rear, and side collision *warnings* alert drivers to hazards, but require drivers to take evasive maneuvers.

Unlike automated enforcement, in-person enforcement is also an active measure as it requires individual officers to make decisions about who is speeding, leaving enforcement of the law up to human judgement and discretion.

Notably, policies could support active measures becoming latent measures. For example, vehicle safety regulations might require passive alcohol detection on steering wheels should the technology be available, or cordon-based speed governors at certain locations in the transportation network.

Education

At the top of the Health Impact Pyramid is educational interventions. This tier is missing in the Hierarchy of Controls but might be codified under "Administrative Controls." Regarding behavioral approaches, Frieden writes "The need to urge behavioral change is symptomatic of failure to establish contexts in which healthy choices are default actions" (Frieden, 2010). We agree and thus place "Education" at the top of the Safe Systems Pyramid.

The focus on behavior change as a symptom of failed healthy contexts applies to public health generally, and transportation specifically. If one needs constant reminders to slow down, stop at red lights, or yield to pedestrians, it is necessary to examine the scenario to determine whether the socioeconomic context or built environment encourage risky behavior. If altering these contexts is not possible, then applying passive or active measures should be explored. However, educational interventions tend to be the least politically controversial, least expensive, and easiest to implement. Educational interventions can contribute to traffic safety programs by raising awareness of new policies (e.g., a speed limit change), promoting safety as a cultural value, helping people navigate the transit system or try walking and cycling, and as a means of teaching the rules of the road. However, they are conditional on individual behaviors, and are susceptible to failures elsewhere in the transportation system. Educational measures can be important and effective when they are complementary to other approaches and combined with efforts from other tiers in the pyramid.

Practical application: safe systems project selection and prioritization

To demonstrate the value of this framework, we apply it to an example Safe Systems program. In this example, a program manager must decide how to prioritize projects and initiatives within their purview, knowing that they must balance the key performance metrics of [presumably reducing] the number of injuries and fatalities each year with limited funding and staff time.

The framework presented here encourages managers of a Safe Systems program to first support those projects that address socioeconomic factors and systemic inequities, as they set the context for transportation. In the U.S., Safe Systems programs typically have not integrated efforts to improve local policies for affordable housing and frequent, reliable transit. But this framework argues that such a siloed approach to transportation safety will not improve safety outcomes; viewing crashes as a public health problem requires those working in transportation safety to consider and attempt to improve the underlying social context in which these crashes take place. It is true that much of the decision-making on socioeconomic factors is outside of the jurisdiction of transportation safety professionals. However, Safe Systems programs and their staff can still be active in these arenas. For example, they can advocate for shared data systems across departments to reduce silos, engage in joint efforts with housing or transit agencies on projects that reduce the travel (e.g. transit-oriented-developments), or "co-sign" relevant policies to indicate support to local and regional governments.

Next, the Safe Systems program manager must prioritize changes to the built environment, focusing on projects that contribute to safety on the city and roadway scales. These must be projects that, through their design (including new design and retrofitting of existing facilities), mitigate the exchange of energy such that when crashes occur, they do not exceed the threshold of human tolerance. Projects that lower prevailing speeds (e.g., chicanes or speed humps), separate users in time and space on higher speed facilities (e.g., leading pedestrian intervals at all intersections, separated bicycle facilities on arterials), and physically protect people or otherwise disperse energy during collisions must be prioritized (Chen et al. 2013; Hu and Cicchino 2020). Often, retrofitting projects are limited in space, funding, or both. When considering which projects to prioritize within a list of possible improvements (often in the form of a "Safe Systems Action Plan," or similar) given constrained resources, program managers should consider those that most mitigate the transfer of energy during a crash.

Further, people and communities that are more likely to be exposed to traffic risk should receive priority in receiving funding or projects. In some cases, this can be a practical integration of the two bottom levels of the Pyramid, but a similar approach can extend to local departments of transportation installing latent safety features to protect their own workers, such as latent safety technology in city owned vehicles, as well as temporary physical barriers for workers present in roadways.

Infrastructure projects often take priority in Safe Systems programs in the US, and the proposed paradigm supports this approach. Less common is a focus on latent safety measures, but our framework shows their importance. Common ways that these programs address this level in the Pyramid is through Automated Speed Enforcement that facilitates lower speeds in urban areas or along a high-injury Network (Wilson et al., 2010). Like socioeconomic factors, however, engineers involved in these programs may not see their role as extending to some of the other areas that are encouraged by this paradigm, like support for speed cameras, which reinforce engineer's design decisions.

Both active measures and educational programming are important elements of a Safe Systems program, but they should not be prioritized over more passive elements of control that can have safety benefits without a great deal of effort from those using the system. When resources allow, an educational campaign that instructs people on how to properly install a child safety seat, for example, can help improve the effectiveness of safety seats. While most Safe Systems education interventions have centered on educating the public, it is worth noting that there are limited examples of Safe Systems education integrating with the education system. For example, educational interventions may be best suited to improving engineering education during undergraduate and graduate schools, as engineering students are the future workforce and leaders of the transportation industries, but research indicates that there may be disparate safety knowledge among engineering majors (Saleh and Pendley 2012). Future research should explore opportunities for integration of these topics in engineering education and professional development so that system designers are trained effectively to create safer environments and understand the Safe Systems approach.

Discussion and conclusions

DeHaven, Gordon, Haddon and others worked to understand the first principles/causes of injuries. Their work is foundational in understanding how to prevent injuries by understanding the different factors that might contribute to traffic injuries, and how to eliminate them. We now know that the agent of injury is kinetic energy and that approaches to prevent or control its transfer to human bodies must be used to prevent traffic injuries. Further, the public health principles of prevention and population level interventions will help prevent serious and fatal injuries.

The traditional frameworks used to design and evaluate Vision Zero programs, roadway safety projects, and other interventions inadequately describe the complexity of road safety. They often attribute outsize effectiveness to behavioral interventions and falsely assign blame to individuals in the roadway environment. The “E’s” framework, the primary framework in American road safety for decades, suggests a false equivalence between different countermeasures, does not incorporate public health principles of prevention and population level intervention, and does not focus on the agent of injury: kinetic energy. Even a more recent approach to roadway safety in the form of the USDOT’s National Roadway Safety Strategy incorrectly directs its focus on the *outcomes* rather than the *cause* of crashes, stating “A Safe Systems approach will guide our actions through a focus on Safer People, Safer Roads, Safer Vehicles, Safer Speeds, and Post-Crash Care” (National Roadway Safety Strategy, 2022). It is crucial for the safety of millions of people who use US roadways every day that future strategies integrate proven public health approaches to injury prevention, instead of reiterating versions of the same strategy that underpins the ineffective “E’s” framework, just using re-worded new phrases.

This pyramid builds on the work of Haddon and others by linking transportation practice to public health thinking and strategy. By using the Safe Systems Pyramid to evaluate Vision Zero and other traffic safety programs, practitioners can (1) prioritize countermeasures by their effectiveness in controlling or preventing the transfer of kinetic energy; (2) assess the population level impact; (3) determine whether individual effort is needed; and (4) support efforts that address the social determinants of health – all using the same framework. Incorporating public health theories into other disciplines can assist engineers and other built environment professionals to apply public health methods.

Codifying and prioritizing interventions in the Health Impact Pyramid does not mean that only one approach is needed. Rather, *the pyramid structure is intended to help engineers and other road safety practitioners understand the population health impact of various interventions*. No single strategy can be effective alone, and transportation professionals must make use of interventions at each level of the pyramid given their jurisdictions. When various preventive measures are used in combination, and to the extent that they influence social norms and culture, they can be more effective than interventions affecting individuals alone. Vision Zero and the Safe Systems approach call for a paradigm shift in transportation safety from spot treatment towards a holistically systemic approach – which is, perhaps controversially, unfalteringly at odds with the perspective of “balancing” trade-offs between mobility of vehicles and safety. To induce such a shift, it is necessary for transportation professionals to understand their roles as public health professionals and incorporate public health principles into their thinking and practice. The Safe Systems Pyramid provides a framework for such thinking.

The Safe Systems Pyramid is of interest to transportation engineers, planners, policymakers, educators, or any professionals that influence the policies put in place to ensure transportation safety. Transportation professionals, however, often lack formal public health training and are unlikely to know how to apply public health ideas systematically or intentionally, even if they share the values of public health practitioners. Frameworks can help professionals bridge gaps between science, values, and practices. The Safe Systems Pyramid can be used to influence and prioritize interventions and policy, as well as educate transportation professionals to adopt a public health consciousness.

Public health practice is founded on the ideas that health problems are preventable when addressed at the population level, and that one should focus on preventing and controlling risk factors while promoting protective factors when possible. These principles are inherent in Safe Systems and Vision Zero policies, which emphasize that deaths are preventable, and that speed is a primary risk factor. Despite these ideas appearing in many Vision Zero plans in the US (Fleisher et al., 2016), these policies lack a simple, cogent framework for prioritizing interventions based on the science of injury prevention and control. By incorporating elements of population health principles from the Health Impact Pyramid and control strategies from the Hierarchy of Controls, the Safe Systems Pyramid codifies the public health principles underlying transportation safety practice.

Engineers have played an important role in public health for centuries, from building sewer systems, to draining swampy areas, to building safer vehicles. The science and values of public health were foundational to that work. Similarly, the principles and science of injury prevention and control are foundational to the work of transportation engineers and planners. The Safe Systems Pyramid is a means of bridging the public health principles inherent within the Safe Systems approach with everyday transportation decisions.

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