Zeroing in on Traffic Fatalities in the United States: Using a Safe System Attribution Schema to Determine Fatal Cases Eliminable by Automated Vehicle Fleet Conversion

Eamon T. Campolettano, John M. Scanlon, Kristofer D. Kusano, Trent Victor

Abstract Previous research from other countries and state-level analyses has assessed how fatalities manifest through a Safe System perspective. Using codified fatality data from 2023 from the National Highway Traffic Safety Administration's (NHTSA) Fatality Analysis Reporting System (FARS), this study characterised elements of the Safe System that featured in fatal cases and explored the extent to which automated vehicles could serve to greatly reduce the current traffic safety burden. The elements of impairment (43.0% of cases), speeding (28.0%), and restraint/helmet misuse/nonuse (53.2%) featured heavily in this fatal dataset, with 29,019 (77.1%) involving at least one of these three elements and 3,468 (9.2% of fatal cases) involving all three of these elements. Slightly more than 8% (3,086 total cases) of fatal cases involved only Safer People features, highlighting the interconnected nature of deviations from the Safe System in fatal cases. This analysis further estimated the potential for automated vehicles to reduce passenger vehicle-related traffic fatalities in the United States by anywhere from 47%-83% from current levels using an elements-based approach. While automated vehicles will not be a panacea for traffic fatalities as shared responsibility is required for a Safe System, designing them in accordance with Safe System principles offers the potential to reduce traffic fatalities in the United States.

Keywords Autonomous Driving Systems, Safe System Approach, Vision Zero

I. INTRODUCTION

After a relative peak in traffic fatalities in 2021, the United States has experienced two consecutive years of decreased annual fatalities (and fatality rates), with 40,901 total for 2023 [1–2]. This still represents a greater number of traffic fatalities than all preceding years dating back to 2007, also reflected at the rate level, highlighting the increasing risk of roads in the United States. While there have been improvements in passenger vehicle occupant protection and safety outcomes, with approximately 5,000 fewer occupants dying annually in 2023 compared to 2007, there has been a marked increase in the traffic fatality burden for vulnerable road users (pedestrians, cyclists, and motorcyclists), who have seen their fatality counts increase by 56%, 65%, and 23%, respectively [1–2]. To that end, the Insurance Institute for Highway Safety (IIHS) began an initiative in 2025 called *30x30* to reduce the number of traffic fatalities in the United States by 30% by 2030 [3].

This initiative bears inspiration from the Vision Zero approach from Sweden that recognises that any death in the road transportation network is unacceptable [4–7]. Since its adoption more than a quarter of a century ago, Sweden has decreased its traffic fatalities by more than 50% [8]. An implicit aspect of Vision Zero is that human biomechanical injury tolerance represents the limiting factor within the road transportation network [4]. The United States Department of Transportation has adopted Vision Zero as the Safe System Approach, a set of five targeted objectives to eliminate crashes resulting in serious injury and fatality: Safer People, Safer Vehicles, Safer Speeds, Safer Roads, and Post-Crash Care [9], hereafter referred to in this paper as Safe System aspects.

A Safe System recognizes that humans make mistakes, but those mistakes should not result in death within the road network. The interplay of humans, vehicles, and roadway infrastructure with speed can serve to accommodate some of these mistakes when crashes occur and provide avenues for appropriate post-crash care to be carried out. A Safer People violation, such as an occupant failing to don their seat belt, need not result in a fatality as a result of a crash, but it does call into action other elements of the Safe System (e.g., a Safer Vehicle with sufficient passive safety features to ride down crash forces or Safer Roads that limit the potential for high

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energy crashes with the roadway environment or other road users). This creates a shared responsibility among, not only roadway users, but also government, industry, and researchers, that acknowledges that serious injuries and fatalities are unacceptable, and humans are an inherently vulnerable member of the human-centered Safe System.

While a core aspect of Vision Zero and the Safe System Approach is a paradigm shift away from placing all blame on the road user and toward a combined, system level interplay of road users, vehicles, and the roadway infrastructure aimed at minimising deleterious traffic outcomes, numerous figures have proliferated over the years which serve to abdicate responsibility for changes to the status quo. Prior to Vision Zero, analysis of crash data from the 1970s in the United States and United Kingdom observed that the road user was a contributor to up to 95% of crashes [10]. More recently, the National Highway Traffic Safety Administration (NHTSA) carried out an analysis of the critical reason (last reason) for collisions investigated as part of the National Motor Vehicle Crash Causation Survey (NMVCCS) and reported that the critical reason was assigned to the driver in 94% of cases [11]. Despite a clearly-stated limitation that the assessment of critical reasons as part of the study was 'not suggestive of the cause of the crash nor of a fault to the driver, vehicle, or environment,' this figure was regularly referenced by high-ranking government officials and agencies in the United States for several years [11]. In 2022, at the behest of the director of the National Transportation Safety Board, reference to this figure was removed from government websites, and, since then, there has been a large-scale effort, by the Vision Zero Network and others, to debunk this myth and move toward a Safe System Approach to assessing the traffic fatality burden, though it still persists in 2026. Notably, researchers have acknowledged the high contribution of human error in traffic collisions but have noted that "according to Vision Zero philosophy, 95% of the solutions are in changed roads, streets or vehicles [12]."

As the forebears of Vision Zero, the Swedish Transport Administration developed a model for considering what traffic violations were associated with traffic fatalities [5][13]. In Sweden between 2016 and 2018, they observed that approximately 58% of traffic fatalities owed exclusively to a mistake or misjudgment by a road user, 16% to lack of restraints/helmets, and 9% to deliberate, severe traffic rule violations (e.g., excessive speeding) [13]. While these proportions have been fairly consistent in Sweden over the last 25 years, the overall number of fatalities in Sweden have dropped from over 500 in 1998 to just over 200 in 2024, with a corresponding rate decrease from 0.79 per 100 million vehicle kilometres traveled to 0.26 [8]. Similar, more granular approaches have been carried out successfully to assess system contributions toward serious injuries and fatalities in Sweden and the United Kingdom [14–15]. More recently, researchers leveraged aspects of the Safe System Approach to consider their association with serious injuries and fatalities in the state of Ohio in the United States [16]. Fewer than 20% of these serious injury or fatal crashes were found to be associated with only a single aspect of the Safe System, with 8% associated with all aspects considered by the authors (Safer People, Safer Roads, Safer Vehicles, and Safer Speeds) [16].

Building on this previous Safe System lens analysis of fatal crashes, this study sought to characterise the combined associations of the various aspects of the Safe System Approach towards traffic fatalities in the United States at the national level. The intent is not to assign blame, but rather to highlight how interconnected the elements of the Safe System are, and how, generally speaking, no single failing is present in a given fatal crash. This is consistent with recent work from Vision Zero leaders that recommended that crash causation and singular cause analyses be replaced with a more holistic, system-level review to ensure that appropriate and robust countermeasures not be overlooked [17].

Beyond this, there is an opportunity to meaningfully reduce fatal outcomes through a combination of conflict/collision avoidance and severity mitigation with ongoing development of advanced safety features for passenger vehicles and expanding deployment of automated vehicles in cities across the United States and world. Accordingly, a secondary objective of this work was to quantify the extent to which automated vehicles, designed with Safe System principles in mind, have the potential to reduce traffic fatalities through a focused assessment of attributable elements observed in crashes.

II. METHODS

Data Source

This study leveraged data from NHTSA's Fatality Analysis Reporting System (FARS) from 2023, the most recent available data at the time of drafting. FARS is a census of fatal motor vehicle crashes occurring in the United States, aggregating state-provided fatal crash information from police reports, vehicle registration data, driving records, death certificates, toxicology reports, and emergency medical service reports [18]. FARS consists of 30 data files, compartmentalising case information across different groupings, with a unique identifier for each case at the state level, with vehicle- and person-specific identifiers also denoted within each case.

Each of the 30 data tables was reviewed to identify encoded variables associated with Safe System attribution. Across all the tables, there is some level of redundant information. In nearly all cases, directly encoded variable information was used to create binary Safe System attribution criteria (Fig. 1, Table AI). In some instances, encoded information was used to create author-developed fields. For example, a variable (*Speed-related)* was created that captured any case in which either there was reported speeding or the driver was cited for a speeding violation (Table AI). Each variable was only assigned to a single aspect of the Safe System deemed most representative, though an argument could be made for additional aspects (e.g., *Speed-related* was deemed an element of Safer Speeds but could reasonably be argued as belonging to Safer People). The Appendix contains specific encoding information for all variables used in this study (Table AI).

For this study, all analysis was aggregated at the case level. In other words, cases involving multiple people or vehicles were flattened into a single row. By way of example, a case which involved two vehicles would be considered as being *Speed-related* if either (or both) of the vehicles was reported to be speeding. Returning to the motivation outlined in the introduction, this analysis choice allows for appropriate consideration of Safe System attribution in fatal cases rather than aiming for a single root cause.

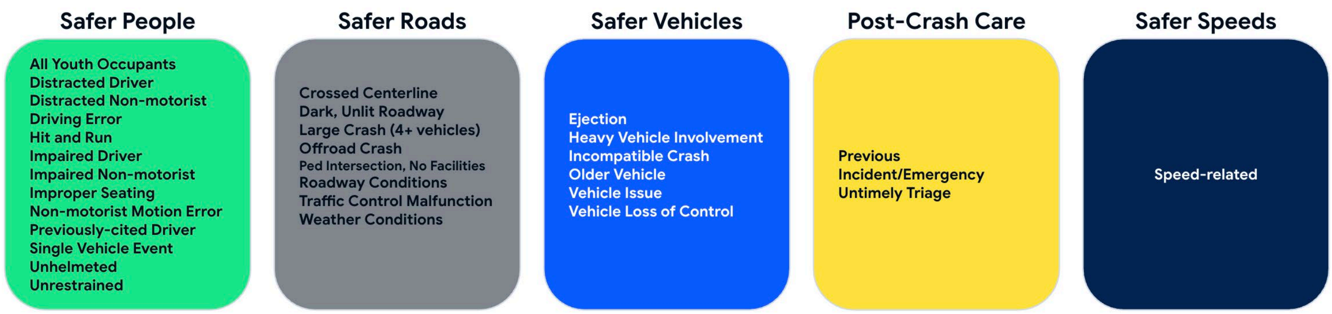

Fig. 1. Safe System attribution schema used for all fatal cases. Specific definitions were based entirely on encoded information, with author discretion used to combine various data elements or identify criteria. See Appendix for specific coding information.

Safe System Attribution

Each of the five objectives (aspects) of the Safe System Approach (Safer People, Safer Roads, Safer Vehicles, Safer Speeds, and Post-Crash Care) were represented in the final set of elements considered, where elements refer to the individually encoded data and aspects represent the higher-level aggregate grouping of elements. While many of the elements are intuitive, such as *Unhelmeted* or *Unrestrained*, some require more context. Elements were only assigned for cases in which they were relevant (e.g., *Unhelmeted* was only assigned in cases involving cyclists or motorcyclists and *Ped Intersection, No Facilities* was only assigned in pedestrian cases).

Within Safer People, the *All Youth Occupants* and *Improper Seating* variables aim to capture elevated risks associated with unsafe behaviors. *All Youth Occupants* aims to capture the increased risk for teen drivers transporting their peers absent an adult by considering cases in which there are multiple occupants in a vehicle and all are below the age of 20 (i.e., a teen driver with younger occupants). Previous research has shown an increased fatality risk for teen drivers transporting their peers compared to driving alone, with this risk increasing with more passengers [19–20]. *Improper Seating* captures those occupants not in seats (either inside or outside of the vehicle) as well as those not in age-appropriate seats (limited to an assessment of front-seated occupants below the age of 13 here). *Hit and Run* was selected as a Safer People element given the legal requirements in the United States surrounding reporting motor vehicle collisions involving injury or fatality, including remaining at the crash scene in such cases. Absconding from the crash scene thus represents a failure to adhere to a Safe System, potentially delaying post-crash care due to lack of timely crash reporting.

Within Safer Roads, *Weather Conditions* was defined to capture environmental conditions in which vision was noted to be obstructed by weather conditions or the atmospheric conditions themselves were associated with decreased visibility or control (i.e., severe crosswinds, fog, or blowing sand). This limited attribution did not capture all times in which there was rain or snow, which could be coincidental rather than attributable (unless explicitly noted). *Roadway Conditions* aimed to capture these attributable effects, as well as those with degraded roadways. Lastly, pedestrian events in which the impact occurred at an intersection without a crosswalk were categorized separately as well given the infrastructure limitations associated with these events.

Within Safer Vehicles, *Crash Incompatibility* captured collision events in which there was vehicle under or override or the involved vehicles were from different gross vehicle weight rating classes (i.e., mass mismatch).

Within Post-Crash Care, the *Incident/Emergency* element was an aggregation of numerous encoded variables (Table AI) to identify instances in which a previous collision or active collision/emergency response were involved. Post-Crash Care necessarily involves making sure that secondary collision events are avoided and additional injuries not created. The *Untimely Triage* variable captured cases in which there was medical treatment and more than 60 minutes passed between the time of the crash and the patient's arrival at a hospital. This was inspired by the golden hour in trauma medicine, whereby prompt surgical intervention within an hour of the injury can considerably reduce the likelihood of death [21]. While these data are not always encoded and the golden hour is more of a guideline encouraging timeliness in emergency response rather than a strict cutoff, insight into the frequency of cases which involve delayed transport can be useful for understanding how the Safe System extends beyond the initial crash event.

Lastly, Safer Speeds attribution was restricted to only those cases in which there was reported or attributable speeding as highlighted above.

Analysis Groupings

Beyond the coding for each case, aggregate analysis was carried out at various grouping levels to assess what absences from the Safe System were present. Visual representation of this analysis was conducted using the *ComplexUpset* package in R [22–23] to highlight (1) what Safe System objectives were represented and (2) what specific elements within these objectives were observed. By taking this macro- and micro-level approach to fatal traffic crashes, it is possible to learn what the most commonly observed elements are. This process was carried out for several different comparisons to evaluate how relevant different elements of the Safe System are for different crashes. Firstly, comparison was done at the agent level, with fatal events involving pedestrians, cyclists, motorcyclists, and vehicle occupants evaluated distinctly. Another comparison considered the rural vs. urban divide (*RURURBAN*), and the last comparison considered roadway location (highway vs. non-highway), with highway defined for events with *FUNC_SYS* values of 1 or 2 (found in the ACCIDENT data file).

Assessing the Potential for Fatality Reductions through Vehicle Safety Advancement

With continued development of advanced safety features and deployment of automated vehicles on public roadways, it is important to contextualise the extent to which the status quo on the roadway may change. This analysis focused on the estimated safety benefit associated with all passenger vehicles in these fatal events being replaced with automated vehicles. For all fatal cases, each of the Safe System attributable elements was considered as being (1) Exogenous (unaffected by automated vehicle fleet conversion), (2) Endogenous (eliminable by automated vehicle fleet conversion), or (3) a combination of these as it relates to automated vehicles (Table AII). Independent of any other elements, unhelmeted cases were considered as being Exogenous given that cyclists and motorcyclists can attain high travel speeds independently and be seriously or fatally injured even absent a collision with a car. On the other hand, the overwhelming majority of fatal single vehicle passenger vehicle crashes should be eliminated with automated vehicles that are designed with Safe System principles, making exceptions for cases where reasonable physical limitations of vehicle control are present (e.g., roadway, vehicle, or weather contributing circumstances). As an additional Exogenous example, a case in which a pedestrian crossed at a roadway intersection when the vehicle had the right of way (with no other involved elements) would be considered as being Exogenous as the only involved elements do not relate to the vehicle in any way. Conversely, a case in which that same pedestrian crossed at a roadway intersection with the right of way and was struck by an impaired driver who was speeding would be considered as being Endogenous as the only involved elements would not be present in a fleet of automated vehicles. It should also be noted that any fatal cases with zero Safe System attributable elements were considered as Exogenous.

For all other cases with some combination of these elements, existing safety effectiveness estimates from the literature were used to approximate the range of cases expected to be addressed. These available effectiveness numbers were used in lieu of a case-by-case consideration given some of the limited granularity within FARS. Specifically, research highlighting the on-road effectiveness of safety technologies, active deployment of automated vehicles, or systematic evaluations of safety benefits were considered. For pedestrians, effectiveness in reducing crashes or injuries of pedestrian automatic emergency braking (AEB) and crash avoidance estimates (9% to 78%) [24–27] and deployed automated vehicles (92%) [28] were used. For cyclists, effectiveness of cyclist AEB and intelligent transport systems (ITS) were used (4% to 55%) [29–31], as were deployed automated vehicles (83%) [28]. For motorcyclists, deployed automated vehicles (80%) [28] and safety benefits estimates related to crash avoidance and motorcyclist AEB (8% to 23%) [32–33] were used. Lastly, for vehicle occupants, AEB (46% to 52%) [27], deployed automated vehicles (42% to 96%) [28], and an estimate for automated vehicle deployment (67%) [33] were used. Beyond these cases, the remaining fatal cases involving only unaddressable elements were quantified as well and presented alongside relevant non-AV-related safety interventions in order to have a complete perspective.

III. RESULTS

The overall sample consisted of 37,654 fatal cases for 2023 from the FARS database, 7,215 involving fatally injured pedestrians, 1,388 involving cyclists, 6,476 involving motorcyclists, and the remaining 22,575 involving vehicle occupants. This figure is smaller than the total number of fatally injured persons (40,901) reported for the U.S. in 2023, as some cases involved multiple fatalities. A greater number of urban cases (22,400) was observed than rural cases (14,938), with the classification not available for a small number of events (316). Using the functional road class designation, 6,047 events were identified as highway events.

Speeding, driver impairment, and lack of seat belt use are often cited as being commonly observed in traffic fatality data. In this study, a more total traffic perspective was taken by also including impairment among non-motorists (pedestrians or cyclists) and unhelmeted cyclists or motorcyclists into this trifecta of risk factors (Fig. 2). Across all roadway users, this trifecta was observed in 9.2% of all fatal cases, with any/all combinations being observed in over 29,000 cases (77.1%), highlighting the strain placed on the Safe System by the combination of these elements. Impairment in combination with lack of protective equipment (seat belt or helmet) was more commonly observed than speeding behavior.

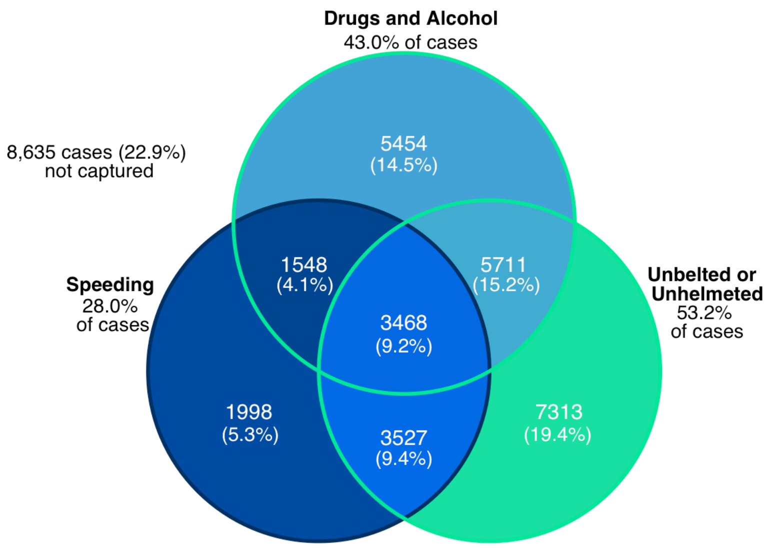

Fig. 2. Proportion of total fatal cases involving speeding, drug/alcohol impairment, unrestrained/unhelmeted people, or the combination of these elements.

When looking at the overall dataset, attributable elements related to Safer People and Safer Vehicles were most commonly observed (Fig. 3). The interplay of people, vehicles, and roadway infrastructure were the most prevalent combination observed in fatal collisions, seen together in 28% of all cases. Expectedly, Post-Crash Care attribution was not observed as the only Safe System aspect in any case. Speeding was observed in 10,541 (28.0%) fatal cases (Table I). Prominent Safer Vehicles attributable elements included vehicles older than 14 years old, which were represented in the majority of fatal crashes (56.1%), and crash partner incompatibility (26.2%). Drug and alcohol impairment was observed in 43% of cases (16,181 total cases), with the vast majority involving driver impairment (13,596). Risky drivers, those who had previously been in a crash or cited within the last three years, were involved in nearly 50% (18,768 total cases) of all fatal cases. Lack of helmet or seat belt use featured in the majority of fatal cases, with 61% of fatal cases involving cyclists and motorcyclists not wearing helmets and 54% of fatal cases involving vehicle occupants not wearing their seat belts. From a Safer Roads standpoint, offroad crashes (38.7% of fatal cases), dark, unlit roadways (27.1%), and events involving at least one vehicle crossing roadway centerlines (19.2%) were most commonly observed (Table I).

TABLE I
Summary of Safe System elements across all fatal cases, sorted by observed frequency

	Count	*Percentage*
Safer People		
Unrestrained	19,236	51.1%
Previously cited driver	18,768	49.8%
Driving error	17,598	46.7%
Drugs/alcohol – Driver	13,596	36.1%
Single vehicle	12,659	33.6%
Non-motorist motion error	6,177	16.4%
Unhelmeted	4,823	12.8%
Distracted driver	3,038	8.1%
Drugs/alcohol – Non-motorist	2,898	7.7%
Hit and run	2,786	7.4%
Multiple occupants, all under 20 years old	1,085	2.9%
Improper seating	826	2.2%
Distracted non-motorist	316	0.8%
Safer Roads		
Offroad crash	14,570	38.7%
Dark, unlit roadway	10,221	27.1%
Crossed centerline	7,217	19.2%
Roadway conditions	901	2.4%
Large crash (>=4 vehicles)	876	2.3%
Malfunctioning traffic control device	697	1.9%
Weather conditions	661	1.8%
Pedestrian intersection, no facilities	417	1.1%
Safer Vehicles		
Older than average vehicle	21,109	56.1%
Crash incompatibility	9,866	26.2%
Vehicle loss of control	7,608	20.2%
Ejection	5,552	14.7%
Heavy vehicle involved	3,194	8.5%
Vehicle mechanical/electrical issue	3,137	8.3%
Safer Speeds		
Speeding-related	10,541	28.0%
Post-Crash Care		
Previous incident or emergency	2,347	6.2%
Untimely triage	1,764	4.7%

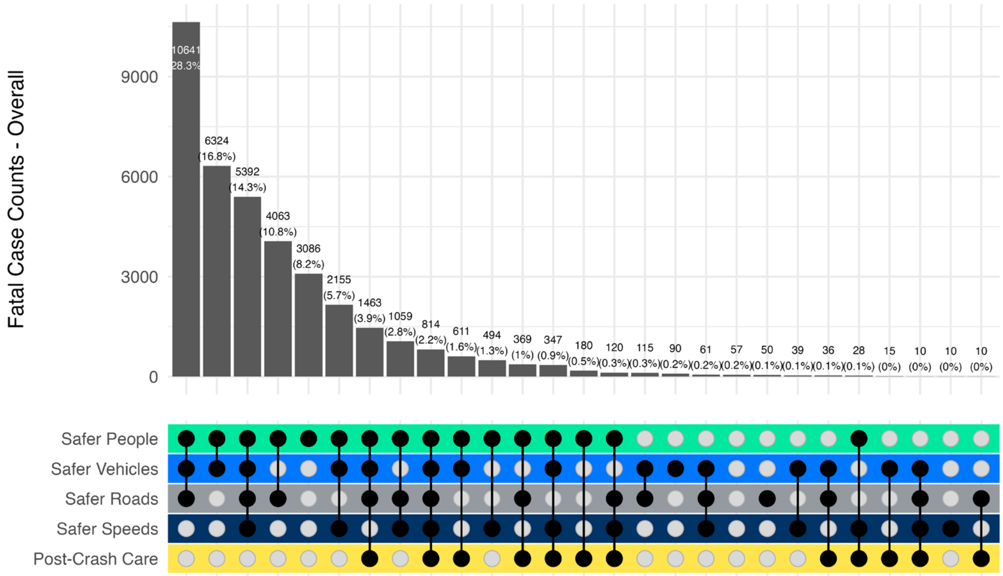

Fig. 3. Safe System attribution across all fatal cases by aspect. Safer People attribution was observed in over 98% of all events, though it was the only aspect in 8.2% of all fatal cases. Minimum of 10 cases for visualisation.

While these high-level descriptive stats are important to note, an understanding of how these specific elements combine in the breakdown of the Safe System in fatal collisions can provide deeper insights as these elements are rarely observed in isolation. Given their heightened vulnerability in general, fatal events involving pedestrians and cyclists were not commonly associated with speeding (Fig. 4). While right of way mistakes involving pedestrians and cyclists were common, they were often observed in conjunction with other elements: dark, unlit roadways, pedestrian/cyclist impairment, and risky drivers, with the additional element for cyclists of being unhelmeted. Interestingly, hit and run collisions also emerged as a notable element (Fig. 4). For motorcyclists, a combination of Safer People elements were most common, as well as speeding and single vehicle, offroad crashes. For vehicle occupants, the large number of potential combinations (from a higher number of relevant Safe System attributable elements) limits the share of most commonly combined features among all fatalities (as shown in Fig. 4 where the most common combination of elements only constitutes 0.7% of cases), though the intersection of Safer Vehicle, Safer People, and Safer Roads elements is pronounced.

More than 46% of fatal rural cases were single-vehicle events, compared to 25% of urban cases. Speeding was identified as an attributable element at a similar rate (28% of urban cases, 27% of rural cases). Fatal cases involving a vehicle crossing the centreline were observed in approximately a third of all rural cases. Fatal highway crashes were associated with a higher concentration of Post-Crash Care elements, observed in over 20% (1,240 out of 6,047) of cases. Of these highway cases involving Post-Crash Care, more than 80% were related to previous incidents or active emergencies, highlighting the increased risk associated with responding to highway events and coinciding with a large share of pedestrian fatal cases (1,147 out of 7215).

Given the large number of potential combinations across the different Safe System attributable elements, it can be difficult to hone in on which are most prevalent in fatal traffic collisions. The UpSet plots shown in Fig. 4 were used to inform element selection for those elements most commonly observed for each agent type. The purpose of this selection was not to mitigate the intersection of Safe System elements, but to highlight some of the most commonly observed breakdowns in the Safe System. For fatal pedestrian collisions, approximately 85% involve a dark, unlit roadway, non-intersection crossings, and/or pedestrian impairment, with about 1 in 8 fatal events involving all three (Fig. 5). The chief element observed in fatal cyclist cases was an unhelmeted rider (59.1%). Interestingly, isolated lack of helmet use was observed to be more common than any other combination of elements. Speeding was a more central element for cases with a fatally injured motorcyclist or vehicle occupant, both in isolation and in combination with impairment or lack of protective equipment (Fig. 5). It should be noted that driving or right of way errors, while more common than some of the highlighted elements, were not included due to (1) limited capacity to ascertain to what extent they played a role in the specific crash and (2) acknowledgment that humans make mistakes and other elements of the Safe System should generally be able to mitigate fatal outcomes.

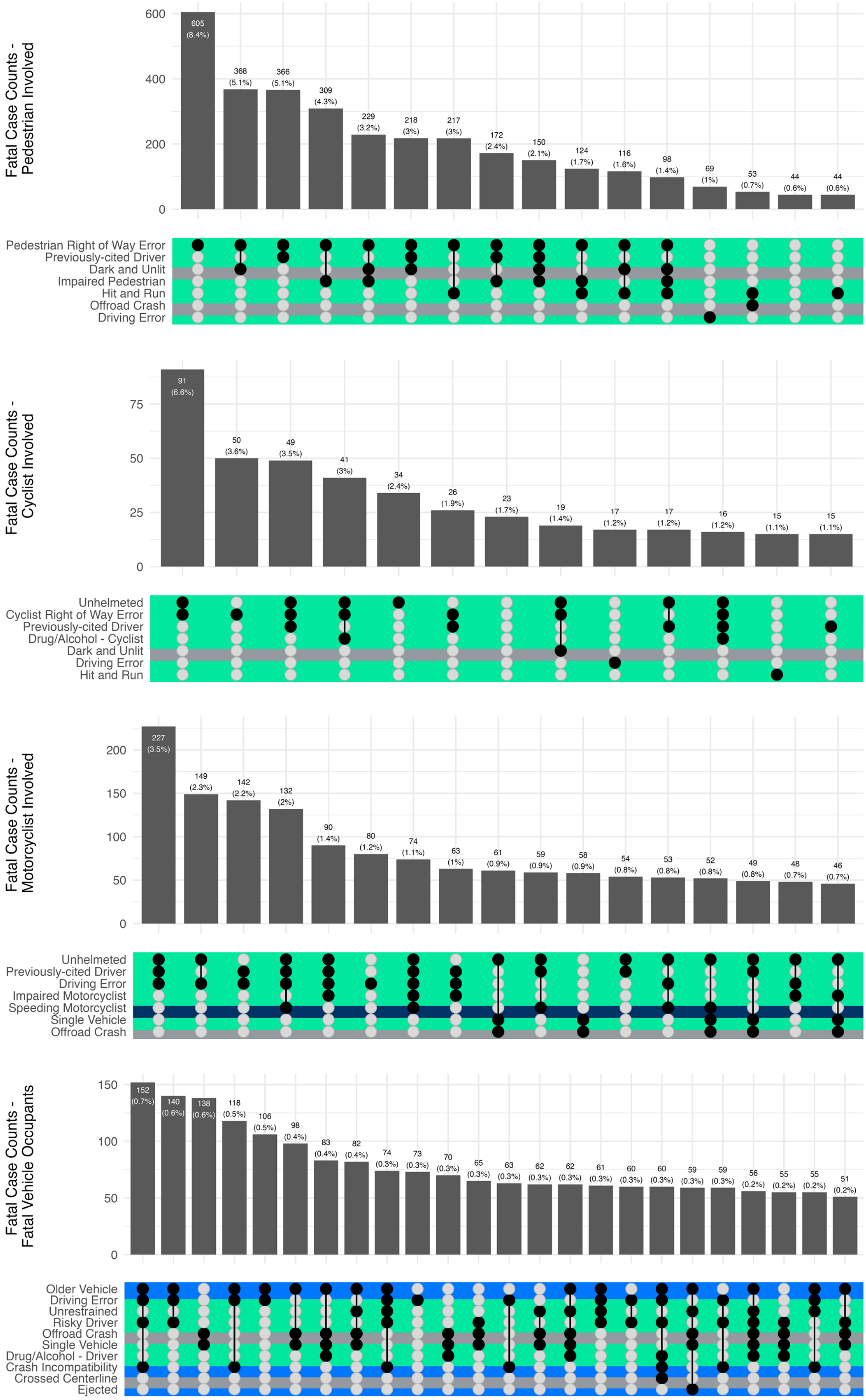

Fig. 4. Safe System attributable elements observed in fatal collisions by agent type. From top to bottom with minimum number of collisions for visualisations in parentheses: Pedestrians (40), Cyclists (15), Motorcyclists (40), and Vehicle Occupants (50).

Fig. 5. Venn diagrams of most common Safe System attributable element combinations by agent type. Clockwise from top left: Pedestrians, Cyclists, Vehicle Occupants, and Motorcyclists

Of the 37,654 fatal cases, there were 34,590 that involved passenger vehicles. Looking at exogenous fatal cases first (cases unaffected by fleet conversion to automated vehicles), there were 3,424 unhelmeted cases involving cyclists and motorcyclists. Further, there were 57 fatal cases without any Safe System attributable elements and 1,366 total fatal cases that only contained exogenous Safe System attributable elements (Fig. 6). This represents a total of 4,847 exogenous cases (14% of passenger-vehicle-involved fatal cases) that are estimated as being unaffected by complete transformation of the passenger vehicle fleet to automated vehicles. A similar approach was taken for assessment of the endogenous fatal cases (cases eliminable by fleet conversion to automated vehicles). Single vehicle passenger vehicle cases (8,202) without reported contributing circumstances from vehicle issues, roadway conditions, or weather were considered as being eliminable by automated vehicles, and a further 2,113 fatal cases only involving endogenous factors were considered eliminable. This resulted in a total of 10,315 endogenous cases (30% of passenger-vehicle-involved fatal cases). The estimated safety benefit for the remaining 19,428 cases involving both endogenous and exogenous elements was assessed separately by agent type (pedestrians, cyclists, motorcyclists, and vehicle occupants) using previously-published safety impact estimates for advanced safety systems, including AEB, ITS, crash avoidance systems, and automated vehicles, as outlined in the methods. As shown in Fig. 6, the total range of eliminable fatal crashes due to complete transformation of the passenger fleet to automated vehicles can be estimated as 16,236 – 28,571, a reduction of 47%-83% against the 34,590 passenger-vehicle-involved fatal cases, and 43%-76% among all 37,654 fatal cases.

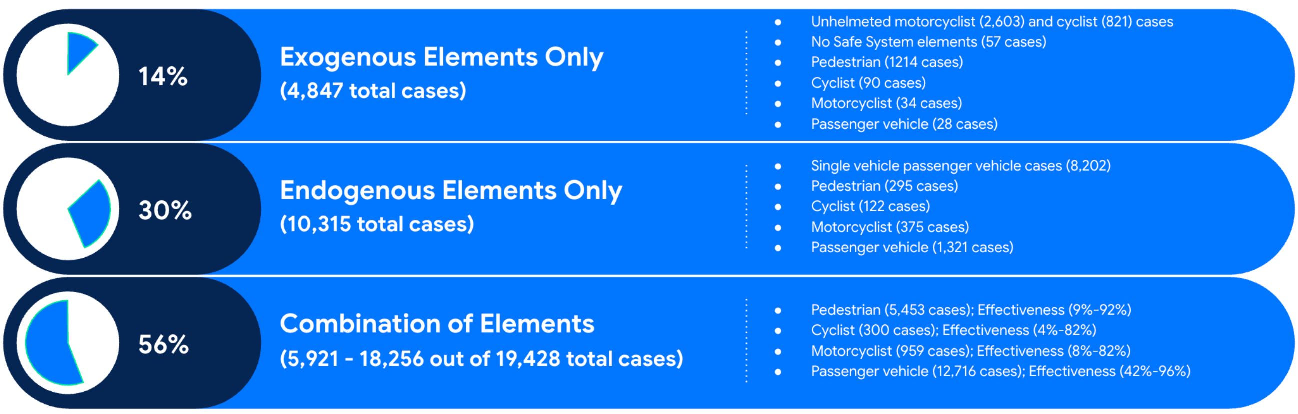

Fig. 6. Estimation of safety benefit associated with automated vehicles based on presence of Safe System attributable elements and estimated system effectiveness from literature.

IV. Discussion

This study mapped observed elements in fatal traffic crashes across the United States to the objectives of the Safe System Approach to inform an evaluation of the potential effects of automated vehicles on the traffic safety burden. Fewer than 9% (3,239 total cases) of fatal cases involved only one aspect of the Safe System. Fewer than 1000 cases (2.4%) involved three or fewer Safe System attributable elements. These low percentages highlight the interconnected nature of these elements in fatal cases. This analysis further revealed the potential for vehicle fleet conversion to automated vehicles to reduce passenger-vehicle-related traffic fatalities in the United States by anywhere from 47%-83% from current levels.

Previous research indicated a driver-related critical reason featured in 94% of all traffic crashes [11]. Using the methodology in this study, over 98% of all fatal cases involved an element attributable to Safer People (Fig. 3), though only 3,086 total cases (8.2%) involved just the Safer People aspect. In other words, while human-related contributing factors feature in nearly all fatal collisions, they are rarely the only element involved. As such, this points to a need for safety interventions that aim to mitigate the harm associated with "human error [12]." It must be noted that this study did not aim to assess causality, merely association, or presence and intersection with other elements of the Safe System.

As the roadway network and vehicle safety have advanced over the last 100+ years, biomechanical injury tolerance largely remains unchanged. Humans are inherently vulnerable, and a Safe System aims to adequately protect humans from serious or fatal injury in the event of a crash. The combination of crash forces and lack of Safe System adherence creates an opportunity for serious and fatal injuries to become more likely (Fig. 7). For example, vehicle airbag deployment implies a sufficient crash impulse imparted to the vehicle such that additional ride-down of forces are required to attempt to mitigate occupant injury, serving as the last line of defense against crash forces. Vehicle airbag deployment was observed in more than half of all fatal cases, including approximately 75% of cases involving fatally injured vehicle occupants. While any single deviation from Safe System adherence may be tolerated, egregious violations or failings involving multiple elements potentially expose humans to crash forces beyond their biomechanical tolerance.

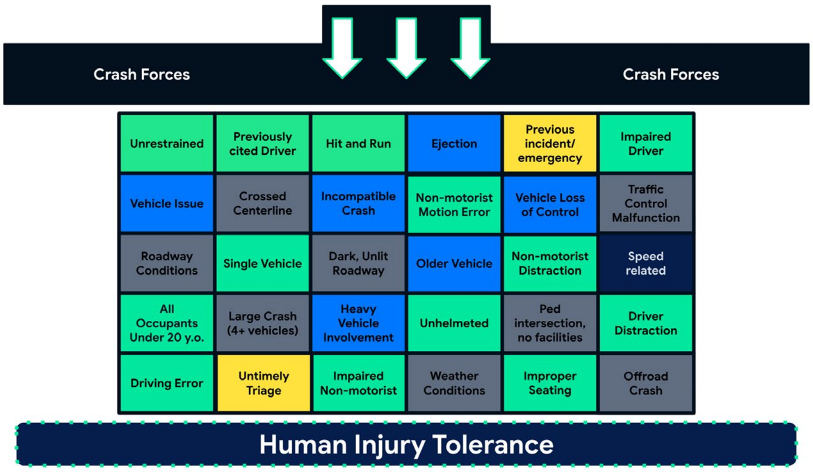

Fig. 7. Visual representation of how fatal injury outcomes become more likely due to the combined effect of high crash forces and lack of adherence to Safe System objectives. Color scheme is as presented in Fig. 1.

Advances in vehicle technology, including continued deployment of automated vehicles, have the potential to greatly reduce traffic fatalities. For example, consider pedestrian fatal cases, over 5,000 of which are associated with both exogenous and endogenous elements (Fig. 6). The most commonly observed elements of non-intersection crossings, pedestrian impairment, and dark, unlit roadways are represented in 85% of cases (Fig. 5). While pedestrian impairment is exogenous to automated vehicle deployment and can be expected to persist, automated driving systems that (1) detect pedestrians even in low light conditions and (2) anticipate the potential for observed pedestrians to cross at locations other than intersections can work to greatly mitigate or reduce serious and fatal collisions involving pedestrians. Research has shown that current pedestrian automatic emergency braking (AEB) system performance varies considerably by lighting condition, with performance lowest at night in lower light settings [34]. Continued refinement of these systems, as well as their continued rollout into vehicle fleets, is needed. Ongoing deployments of automated driving system equipped vehicles in cities in the United States have shown marked decreases of over 90% for injurious collisions involving pedestrians compared to human drivers in those same cities, highlighting both collision avoidance and collision severity mitigation aspects, with no indication of reduced performance under different light conditions [28][35]. While not all automated systems will behave in the same manner, this evidence points to the great potential for aggregate harm reduction for pedestrians with continued advancement in this space. This same line of thinking extends to other types of road users as well.

It is also important to contextualise the fatal events that are only associated with elements exogenous to improvements in passenger vehicle safety and technology. That only 57 out of 37,654 fatal cases (0.2%) involved no Safe System attributable elements highlights that the breakdown of Safe System adherence is what results in traffic fatalities, usually across multiple aspects. The volume of single vehicle cases involving motorcyclist fatality, as well as the large number of unhelmeted cyclist and motorcyclist fatal cases speak to a need for improved safety interventions for these vulnerable road users unrelated to passenger vehicle safety development. Combined, these represent 5,902 fatal cases (15.7%), a sizable portion of the total fatality burden. While not legally required in some states (in the case of motorcycles) or for adults at all (in the case of bicycles), research has consistently shown the protective capacity of helmets to mitigate head injuries, often associated with fatal outcomes [36–41]. National assessment of motorcyclist helmet use through the 2023 National Occupant Protection Use Survey found that over 91% of motorcycle riders used some kind of helmet, though this rate was found to be markedly lower (72%) in states without legal requirement for helmet use [42]. Absent legal requirements after childhood, cyclist helmet use is expectedly much lower, with multiple estimates from 2012 indicating fewer than 30% of riders always wearing their helmet, and approximately 50% reporting never wearing a helmet when riding [43–44]. With over 61% of fatal cyclist and motorcyclist cases involving unhelmeted riders, continued education and intervention is needed on this front. In the same vein, the large number of fatal, single vehicle motorcyclist cases (2,333 [6.2%]) in the U.S. are likely exacerbated by the lack of federal regulations surrounding anti-lock braking systems (ABS) or electronic stability control (ESC) on motorcycles. The European Union mandated motorcycle ABS for all motorcycles exceeding 125 cm^3 from 2016 onward, stemming from field data showing reductions in injury crashes between 24% and 34% across multiple countries, and IIHS has pushed in recent years for similar regulations in the United States [45–47].

Often overlooked in consideration of changes to the traffic network toward reducing fatalities, Post-Crash Care represents a key part of the Safe System that can mitigate further harm or fatal outcomes with appropriate clearance of active scenes and transport to medical facilities. While nearly all states having *Move Over* laws when approaching emergency vehicles on the roadway, fatal collisions as part of previous collisions, post-crash response, or active scenes still remain (over 6% of all cases). Similarly, timely triage is an important aspect of working to limit further harm from crash-induced injuries and avoid fatal outcomes. Though EMS time data was not available for all states in FARS, this analysis still indicated that nearly 5% of all fatal cases involved delivery to the hospital in excess of 60 minutes (a stand-in for timely response rather than an indication of deleterious outcomes outside this time window). Of the 15 states with more than 10% of their fatal cases meeting this criterion for slower triage, all but four had the majority of their fatal cases occur in rural-designated areas. This is noteworthy given the increasing strain placed on rural healthcare in the U.S., with over 150 rural hospital closures since 2010 and research highlighting slower EMS response times for patients in rural areas (not specific to traffic trauma) [48–50]. These likely portend an increasing importance of establishing appropriate Post-Crash Care in the coming years. One potential avenue for this is continued development and widespread adoption of Advanced Automatic Crash Notification (AACN) systems. While systems like this (e.g., OnStar) exist in the United States, they are not ubiquitous or regulated, as is the case in the European Union, where the eCall system has been mandatory in passenger vehicles since 2018 to automatically alert emergency response centres in instances of serious crashes. Research has highlighted the potential for decreased response time and mortality risk associated with these systems [51–52]. Similarly, automated vehicles that can transmit this information may be able to help in the interim as regulations catch up, which may also involve infrastructure improvements on the emergency response side to accommodate this data pipeline. As an additional example beyond post-crash response, consider the Data for Road Safety (DRTS) consortium in Europe, a multi-national endeavor leveraging vehicle data for real-time sharing of safety-relevant roadway conditions, such as black ice, fog, flash floods, or roadway debris, which could serve to prevent cases involving these factors through advanced notification.

The potential for safety benefits of continued advancement in passenger vehicle automation and safety technology highlighted here is really predicated on a commitment to Safe System Approach objectives and principles. Driving systems which (a) encourage adherence to existing roadway speed limits and safe speeds for roadway conditions, (b) utilise defensive driving in anticipation of potential conflicts, (c) provide appropriate clearance to the most vulnerable roadway users (those outside the vehicle), and (d) are free of driver impairment and distraction, serve to not only mitigate the potential for collision events but also the severity potential in the event of a collision. By not speeding, whether through roadway design, automated driving system programming, or intelligent speed assist features, the overall energy required to be dissipated in the event of a collision is reduced compared to when speeding is present, in addition to increasing time available for response in order to avoid conflicts or collisions [53–54]. Foundational elements like these can stand as inherent reduction against crash forces and other violations in Safe System adherence in order to reduce traffic fatalities. As the potential safety benefit analysis showed, an estimated 47%-83% of fatal passenger vehicle involved cases could be eliminated by complete conversion of the fleet to automated vehicles. While the large estimated effect of AVs is encouraging, this work also highlights that AVs are not a panacea for the traffic fatalities in the U.S. Instead, this work can serve as a model of the safety potential afforded by designing vehicle safety advances with the Safe System in mind. It also highlights that approaches taken toward automated vehicles or advanced vehicle safety can have a variable impact, and careful evaluation of the safety performances of these developing technologies is a key part of the overall safety narrative.

There are several limitations of this study to note. First, there is inherent variability in fatal injury outcomes. The same offroad crash that resulted in a fatality due to striking a rigid object may have not resulted in a fatality on other stretches of the same roadway without exposure to offroad objects. Beyond this variability, a further limitation is the censoring associated with in-field observations of injury outcome data. For every road user involved in a collision in FARS, there is no way of knowing how much less severe an event could have been and avoided a fatality. Further, the fatal outcome data provide insights into what types of Safe System attributions are present within cases but do not provide broader context into the overall exposure of these elements. Appropriate consideration involving fatal crash rates would involve both exposure data (e.g., mileage) and more societal level quantification of these factors (e.g., frequency of DUI/DWI violations rather than strictly those observed in fatal traffic cases). For these reasons, it is important to not over-index on specific elements in a given fatal crash or prescribe causality in the absence of a thorough case investigation. This study also considered only fatal cases from a single year (2023); while commonly reported elements such as lack of restraint use, speeding, and driver impairment are fairly stable year-to-year, we would expect small differences in our results when applying this methodology to additional crash years or to other countries. Additionally, this study leveraged author-developed Safe System attribution for each case based on encoded information from FARS. While FARS represents the gold standard for U.S. fatal crash data, there are still accuracy limitations associated with coding errors, either from transposing from police reports to the database or in the original police report/investigations for individual cases. Effort was taken to limit categorisation to objective elements or instances with specific contribution, though the potential for coincidental elements to be captured cannot be ruled out. Related to the estimated safety benefit involving conversion of the passenger vehicle fleet to automated vehicles, the simplifying assumptions used are meant to provide a reasonable range, while a more systematic analysis on a case-by-case basis would be anticipated to yield a more accurate estimate.

V. CONCLUSIONS

This study characterised how elements of the Safe System featured in fatal cases using data from the United States in 2023. Further, it explored the extent to which automated vehicles could serve to reduce the current traffic safety burden. While Safer People elements were observed to feature in over 98% of fatal cases, they were rarely the only element involved, pointing to the need for safety interventions that also aim to mitigate the harm associated with human-related contributing factors. This work, focused on fatalities, adds to the growing body of literature aimed at quantifying the potential safety impact associated with automated vehicles. This analysis, focused on Safe System attributable elements observed in fatal cases, found that 47%-83% of passenger-vehicle-involved fatal cases (43%-76% of all traffic fatalities) could be eliminated through automated vehicle ubiquity and designing them with Safe System and Vision Zero principles.

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VII. APPENDIX

As outlined in the main body of the manuscript, this work leveraged existing fields in the FARS database for all analysis. Table AI provides information on the specific data fields and values used in this analysis. These study variables are grouped by Safe System objective grouping and are presented in alphabetical order.

Table AII presents the variable groupings for the portion of the analysis related to the potential for automated vehicles to address traffic fatalities. For example, automated vehicles can be designed to follow existing roadway speed limits, so speeding is considered as *Endogenous*, where something like the physical condition of the roadway is outside the control of an automated vehicle and is deemed *Exogenous*.

TABLE AI
Definition of study variables based on FARS encoding

Study Variable Name	FARS Data Table	FARS Encoded Variable	FARS Encoded Value or Criteria
		Safer People	
Distracted driver	DISTRACT	DRDISTRACT	NOT (0, 16, 96, 99)
Distracted – non-motorist	PERSONRF NMDISTRACT	NMCC NMDISTRACT	6 NOT (0, 96, 99)
Driving error	VIOLATN DRIVERRF	VIOLATION DRIVERRF	IN (2:6, 9:10, 31:39, 41:49, 51:59, 61:69) IN (6, 8, 18, 20:22, 26:36, 38:51, 54, 102:103)
Drugs/alcohol - driver	VIOLATN DRUGS	VIOLATION DRUGRES	IN (11, 12, 13, 14, 19) NOT (0, 1, 9995, 9997, 9998, 9999)
Drugs/alcohol – non-motorist	NMIMPAIR DRUGS	NMIMPAIR DRUGRES	IN (1, 2, 8, 9, 96) NOT (0, 1, 9995, 9997, 9998, 9999) and VEH_NO = 0
Hit and run	VEHICLE	HIT_RUN	1
Improper seating	PERSON	SEAT_POS, AGE	SEAT_POS IN (51:56) OR AGE < 13 AND SEAT_POS IN (11:13, 18:19)
Multiple occupants, all under 20 years old	PERSON	VEH_NO, AGE	More than 1 occupant in a given vehicle, with all occupants <= 20 years old
Non-motorist motion error	NMCRASH	NMCC	IN (1:5, 9:12, 15:18, 20)
Pedestrian non-intersection	PBTYPE	PEDLOC	3 or 4 and PERTYP = 5
Previously cited driver	VEHICLE	PREV_ACC PREV_SUS1, 2, or 3 PREV_DWI PREV_SPD PREV_OTH	NOT (0, 98, 99, 998) NOT (0, 99, 998) NOT (0, 99, 998) NOT (0, 99, 998) NOT (0, 99, 998)
Single vehicle	VEHICLE	VEH_NO	Only 1 unique vehicle and case does not involve pedestrian or cyclist
Unhelmeted	PERSON SAFETYEQ	HELM_USE NMHELMET	IN (5, 16, 19) and PER_TYP = 1 1 and PER_TYPE IN (6:9)
Unrestrained	PERSON	REST_USE	20
		Safer Roads	
Crossed centerline	VSOE	SOENAME	*Crossed Centerline*
Dark, unlit roadway	ACCIDENT	LGT_COND	2
Large crash (>4 vehicles)	VEHICLE	VEH_NO	4 or more vehicles in crash

Malfunctioning traffic control device	VEHICLE	VTRAFCON VTCONF_F	NOT (0, 97, 99) IN (1, 2, 4)
Offroad crash	ACCIDENT VEHICLE NMPRIOR PBTYPE PBTYPE	REL_ROAD PCRASH5 NMACTION PEDPOS BIKEPOS	IN (2:8, 10, 12) IN (4, 5) IN (3, 5, 6, 8, 16) IN (5:8) IN (3:6)
Pedestrian facilities absent	PBTYPE PBTYPE	PBCWALK PBSWALK	0 0
Pedestrian intersection, no facilities			*Pedestrian non-intersection* AND *pedestrian facilities absent*
Roadway conditions	DRIVERRF MANEUVER VISION CRASHRF	DRIVERRF MANEUVER VISION CRASHRF	IN (77:79, 81:82, 87) 2 IN (3:5) IN (1:7, 24, 25, 30, 31)
Weather conditions	VISION WEATHER	VISION WEATHER	IN (1, 8) IN (5:7)
		Safer Vehicles	
Crash incompatibility	VEHICLE	GVWR_FROM UNDEROVERRIDE	More than 1 distinct, known weight rating IN (1, 2)
Ejection	PERSON	EJECTION	IN (1:3)
Older than average vehicle	VEHICLE	MOD_YEAR	Model year 2011 or earlier
Vehicle loss of control	VEHICLE	PCRASH2 PCRASH4	IN (1:9) IN (2, 3, 4, 5, 7)
Vehicle mechanical/electrical issue	FACTOR VIOLATN DRIVERRF VISION	VEHICLECC VIOLATION DRIVERRF VISION	NOT (0, 99) IN (81:89) IN (56:57, 80, 88) IN (2, 9:14)
		Safer Speeds	
Speeding-related	VEHICLE VIOLATN	SPEEDREL VIOLATION	IN (2:5) IN (21:25, 29)
		Post-Crash Care	
Previous incident or emergency	ACCIDENT VEHICLERF PVEHICLESF DRIVERRF CRASHRF VEHICLERF PVEHICLESF VEHICLE PERSONRF NMPRIOR	WRK_ZONE VEHICELSF PVEHICLESF DRIVERRF CRASHRF VEHICELSF PVEHICLESF P_CRASH1 PERSONRF NMACTION	IN (1:4) 41 41 IN (16, 37, 94:97, 104, 105) IN (10, 19, 20, 23, 26, 27) IN (33, 39, 42) IN (33, 39, 42) 7 IN (53:55, 90, 102) IN (10, 12)
Untimely triage	CRASH	HOUR, MINUTE, HOSP_HR, HOSP_MN	More than 60 minutes between arrival at hospital and time of crash

TABLE AII
Summary of Safe System elements grouped by potential for automated passenger vehicles to address

Endogenous	***Combination***	***Exogenous***
Single Vehicle	Unrestrained	Unhelmeted
Distracted Driver	Dark, Unlit Roadway	Non-motorist Right of Way Error
Drugs/Alcohol – Driver	Ejection	Drugs/Alcohol – Non-motorist
Hit and Run		Distracted Non-motorist
Driving Error		Roadway Conditions
Risky Driver		Pedestrian Intersection, no Facilities
All Young Occupants		Large Crash
Improper Seating		Traffic Control Malfunction
Offroad Crash		Weather Conditions
Crossed Centerline		Crash Incompatibility
Older Vehicle		Vehicle Mechanical/Electrical Issue
Speeding-related		Vehicle Loss of Control
		Heavy Vehicle Involved
		Previous incident/emergency
		Untimely Triage