Understanding Vulnerable Occupants in Vehicles: A Retrospective Analysis

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Abstract This study investigates occupant vulnerability in motor vehicle crashes by examining situational, vehicle-related, and demographic factors influencing injury severity. While research on road safety has traditionally focused on vulnerable road users outside vehicles, certain occupants within vehicles may also face an elevated risk of serious or fatal injury. A retrospective analysis of Ohio traffic crash data (2017–2023) was conducted to assess the relationships between crash characteristics, vehicle type, seating position, and occupant demographics (age, sex, body mass index) with injury severity outcomes. The findings indicate that single-vehicle and angle crashes are associated with the highest frequencies of suspected serious and fatal injuries. Additionally, males, young adults (ages 21–40), and individuals classified as obese are disproportionately represented among fatalities. Drivers sustain the highest injury probabilities across all severity levels, while rear-seat occupants experience comparatively lower probabilities. These results underscore the necessity of targeted safety interventions, including improvements in vehicle design, crash avoidance technologies, and occupant protection systems tailored to at-risk populations. The study provides data-driven insights to inform policy development and engineering strategies aimed at reducing disparities in crash outcomes and enhancing overall vehicular safety.

Keywords Demographics, Occupant Vulnerability, Retrospective Analysis, Safety Strategies, Vehicular Crashes

I. INTRODUCTION

In road safety research, the term vulnerable road users (VRUs) traditionally refers to pedestrians, cyclists, and motorcyclists—individuals outside of vehicles who lack protective structures and are therefore at greater risk of severe injury or fatality in crashes. Efforts to improve traffic safety have largely focused on mitigating risks for these groups through infrastructure improvements, protective gear, and policy interventions [1–5]. However, vulnerability is not limited to those outside the vehicle. Within vehicles, some occupants may face an elevated risk of serious injury or death due to demographic, situational, or vehicle-related factors. While modern safety technologies such as airbags and advanced restraint systems have significantly improved overall crash survivability, they may not provide equal protection to all occupants, particularly those whose body size, seating position, or other characteristics differ from the standardized conditions under which safety features are designed and evaluated.

Understanding which vehicle occupants are at heightened risk, and why, is critical for improving automotive safety and reducing disparities in crash outcomes. Previous research has identified that certain factors—such as age, sex, and BMI—influence injury severity in crashes, yet the extent to which these factors interact with vehicle type, seating position, and crash dynamics remains an area requiring further exploration [6–16]. For instance, young adult males are frequently overrepresented in suspected serious and fatal crashes, yet their vulnerability may be tied to behavioral factors such as risk-taking tendencies and higher exposure rates rather than solely physiological susceptibility [6][17]. Similarly, individuals with obesity have been shown to experience more severe injuries in crashes, possibly due to factors such as suboptimal safety belt fit or underlying health conditions that may complicate injury recovery [8–10]. Therefore, the objective of this study is to determine whether certain vehicle occupants face a heightened risk of suspected serious injury or fatality compared to others and to identify the key factor intersections contributing to this increased vulnerability.

By expanding the concept of vulnerability beyond vulnerable road users (VRUs) to include at-risk vehicle occupants, this research provides critical insights into crash injury risk variability and applies a conceptual framework informed by the Safe System Approach (SSA) for identifying vulnerable occupants. This framework systematically examines key demographic, situational, and vehicle-related factors that contribute to injury

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severity, using the SSA principles to structure both the analysis and the interpretation of findings. Using a retrospective analysis of Ohio traffic crash data, the relationships between manner of crash, vehicle type, seating position, sex, age, and BMI were analyzed with non-severe injury, suspected serious injury, and fatal injury levels. Ultimately, this research aims to bridge existing knowledge gaps in occupant vulnerability, providing data-driven insights that can guide advancements in vehicle safety design, policy development, and educational initiatives to protect the most at-risk vehicle occupants on the road.

II. METHODS

A retrospective analysis of Ohio traffic crash data (2017–2023) was conducted to examine incidents involving non-severe (possible or suspected minor) injuries (n = 550,616), suspected serious injuries (n = 42,469), and fatalities (n = 6,334). This dataset includes all reported crashes in the state of Ohio throughout the period of 2017–2023, ranging from property damage only to fatal crashes. The crash data are compiled using reports submitted by law enforcement to the Ohio Department of Public Safety (ODPS) [18]. Using a standardized crash report form (OH-1), law enforcement document key details at the scene, allowing for a large and consistent dataset. Vehicles that could not be VIN verified through the National Highway Traffic Safety Administration (NHTSA) VIN Decoder [19] were excluded.

All data cleaning, statistical analyses, and data visualization were performed in R v. 4.3.2 [20]. The distribution of non-severe injuries, suspected serious injuries, and fatalities was analyzed in association with manner of crash (angle, head-on, rear-end, sideswipe opposite direction, sideswipe same direction, not collision between two motor vehicles in transport [i.e., single-vehicle crashes]), vehicle type (passenger car, multipurpose vehicle, truck), seating position (front or second right or left side), and occupant demographics (age, sex) (Injury Severity Definitions, Table I). Individuals with missing, unknown, or low-frequency values for these variables, as well as motorcyclists (n = 20,623), were excluded from visualizations to highlight occupant data, preserve interpretability, and avoid distortion from sparse categories. However, they were retained in the overall injury totals to ensure that frequency counts and injury probability estimates accurately reflected the full dataset without underrepresenting the total injury burden. For each level of these variables, the frequency of each injury severity was counted, and its percentage of the injury severity total was calculated. Table AII provides a list, and definitions of all variables included in this study [20–23].

Upset plots generated using the R package *ComplexUpset* [24] were used to visualize the most frequently occurring intersections of variable levels within suspected serious injuries and within fatalities. To further assess injury risk, proportional odds logistic regression was performed using the R package *MASS* [25] to estimate the predicted probability of injury severity (suspected serious injury or fatality) for each variable combination. As an example, the upset plot in the appendix (Fig. A1) visualizes the intersections between a select combination of variables, showing the frequency (black bars, bottom) and predicted probability (blue bars, top) of suspected serious injury for their intersections. This is an abridged version of the full upset plot (Fig. 6), displaying only the variation in age group for male drivers of passenger cars in single vehicle crashes. Young adult males are the most common age group in this scenario, with 1,606 suspected serious injuries, accounting for 3.8% of all suspected serious injuries. Their predicted probability of serious injury in this scenario, as opposed to non-severe injury or fatality, is 11.3%. Older adult males in these circumstances are comparatively rare, accounting for 0.6% of all suspected serious injuries, but their predicted probability of serious injury is the highest, at 13.2%. In other words, older adults are less frequently found in this scenario but have a higher risk of serious injury when this type of injurious crash does occur. This contrast shows that less common road users can represent more vulnerable populations.

TABLE I
DEFINITIONS OF INJURY SEVERITY LEVELS

Injury Severity Level	Definition
Non-Severe	Combined category of both Possible Injury (Any injury recorded or claimed which is not a fatal, serious injury, or minor injury. Possible injuries are those that are reported by the person or are indicated by his/her behavior, but no wound or injuries are readily evident) and Suspected Minor Injury (Any injury that is evident at the scene of the crash, other than fatal or suspected serious injuries)
Suspected Serious Injury	Any injury other than fatal which results in one or more of the following: Severe laceration resulting in exposure of underlying tissues/muscle/organs, or resulting in significant loss of blood, broken or distorted extremity (arm or leg), crush injuries suspected skull, chest or abdominal injury other than bruises or minor lacerations, significant burns (second and third degree burns over 10% or more of the body) unconsciousness when taken from the crash scene, or paralysis
Fatal	Any injury that results in death within 30 days after the motor vehicle crash in which the injury occurred

III. RESULTS

Frequency Distributions of Crash and Demographic Variables

The analysis of Ohio crash data revealed significant trends in injury severity across various crash and demographic variables. The manner of crash demonstrated key trends in frequencies of non-severe, suspected serious, and fatal injuries (Fig. 1, Table AV). Non-severe injury was most prevalent in angle crashes (35.2%), followed by rear-end collisions (29.5%), and single-vehicle crashes (20.1%). Single-vehicle and angle crashes were associated with the highest frequencies of suspected serious and fatal injuries. Specifically, the highest frequencies of suspected serious injuries were associated with single-vehicle (31.1%), angle (26.9%), head-on (11.4%), and rear-end (10.8%) crashes. Single-vehicle crashes also accounted for the highest proportion of fatalities (36.6%), again followed by angle (19.8%), head-on (15.7%), and rear-end (6.5%) crashes. Sideswipe crashes in the same direction and opposite direction each accounted for less than 4% of non-severe, suspected serious, and fatal injuries. Notably, single-vehicle and head-on crashes were characterized by larger contributions to the fraction of suspected serious and fatal injuries than to non-severe injuries. All other crash types contributed relatively more to non-severe injuries.

Vehicle type also exhibited trends in the distribution of injury severity. Passenger cars were involved in the majority of non-severe (50.5%), suspected serious (44.7%), and fatal (43.8%) injuries, likely reflecting their prevalence on the road (Fig. 2, Table AVI). Multipurpose vehicles (MPVs) displayed the same pattern of relatively larger contributions to non-severe injuries (36.4%) compared to suspected serious injuries (27.6%) and fatalities (23.5%). Conversely, trucks contributed a relatively larger fraction to fatalities (12.5%) and suspected serious injuries (10.9%) than to non-severe injuries (9.7%).

Analysis of seating position (Fig. 3, Table AIV) allowed differentiation of drivers (front left side) from occupants located in other seats. This analysis focused on the front and second row right and left seats, as less than 1% of non-severe, suspected serious, or fatal injuries were associated with occupants in other seating positions. Drivers were overrepresented in all injury severity levels, accounting for 71.1% of non-severe injuries, 63.1% of serious injuries, and 62.2% of fatalities. Following drivers, the second most frequent seating position associated with injury was the front passenger (front right side), accounting for 14.8% of non-severe injuries, 13.5% of suspected serious injuries, and 12.2% of fatalities. Second row seating positions on the left and right sides each represented less than 5% of non-severe, suspected serious, and fatal injuries. All seating positions contributed relatively more to non-severe injuries than to suspected serious injuries or fatalities.

Finally, demographic factors of age and sex showed clear trends with injury severity (Figs. 4–5, A2, Table AIII). Demographic analyses demonstrated increased vulnerability for certain sex (Fig. 4, Table AIII) and age (Figs. 5, A2, Table AIII) groups. Males accounted for a greater proportion of fatal (52.7%) and suspected serious (45.3%)

injuries, while females comprised a larger fraction of non-severe injuries (52.7%). Age trends revealed that young adults (ages 21–40) had the highest injury rates, comprising 35.0% of non-severe injuries, 32.4% of suspected serious injuries, and 26.8% of fatalities. They were followed by middle-aged adults (ages 41–60), who accounted for 24.2% of non-severe injuries, 21.5% of suspected serious injuries, and 21.1% of fatalities. Overall, a steady decline in injury frequency was observed before age 21 and after age 61, decreasing for older adults (ages 61–79) and teens (ages 12–20), followed by elderly adults (ages 80+) and youths (ages 0–12). The relative contributions to injury severity were higher for non-severe injury in middle-aged and younger groups, but higher for fatality in older adult and elderly age groups.

Predicted Probabilities of Injury Severity Across Variable Combinations

To investigate interactions between these crash and demographic variables in injurious crashes, upset plots visualized the percentages of serious injury (Fig. 6) and fatality (Fig. 7) represented by frequent variable combinations, along with the corresponding predicted probability of that injury severity level. To simplify visualization, variable combinations were displayed and analyzed only if they were associated with at least 0.5% of suspected serious injuries (212 occurrences) or 0.5% of fatalities (32 occurrences).

The most frequent combination of variables within suspected serious injury (Fig. 6) was a young adult male driver of a passenger car in a single-vehicle crash (3.8%). While this scenario was the most frequent source of suspected serious injury, it had a moderately low predicted probability of suspected serious injury (11.3% probability). In other words, other combinations of variables were less common, but could have a higher probability of suspected serious injury when they did occur. The highest risks of suspected serious injury were associated with male drivers of passenger cars in head-on collisions, for middle-aged (18.4% probability) and young adult (17.2% probability) age groups. Variable combinations across age, sex, and vehicle type were associated with an increased probability of suspected serious injury if they involved head-on crashes (13.8–18.4% probability) or single-vehicle crashes (7.3%–13.2% probability). Isolating this upset plot to each vehicle type (Figs. A3, A5, A7) and matching person demographics within manner of crash where such combinations were available, slight elevations in the probability of suspected serious injury were generally observed for males over females, and with increasing age. For example, in passenger cars (Fig. A3), the predicted probability of suspected serious injury in an angle crash was elevated for males over females by 1.4% in young adults, 1.6% in middle-aged adults, and 1.8% in older adults. This demographic disparity increased for passenger cars in single vehicle crashes, which had an overall higher risk of suspected serious injury, with males exceeding females by 2.4% in young adults and 2.6% in middle-aged adults. The most injurious manner of crash, head-on, could only compare young adults, where the risk to males exceeds females by 3.4%. A similar trend was observed for the same comparisons in multi-purpose vehicles (MPVs) (Fig. A5). In angle crashes, the predicted probability of suspected serious injury increased for males compared to females by 1.6% in young and middle-aged adults, and 1.8% in older adults. In single vehicle crashes, this disparity again increased, with an elevated risk for males over females of 2.2% in young adults and 2.3% in middle-aged adults. The only available comparison for head-on crashes was middle-aged adults, for which males exceeded females by 2.2% predicted probability of suspected serious injury. Females in undiscussed age groups did not reach the threshold of 0.5% of all suspected serious injuries for comparison to their male counterparts. Similarly, no manner of crash involving a truck (Fig. A7) exceeded 0.5% of suspected serious injuries for females of any age group.

The most common variable intersection within fatal injury (Fig. 7) remained a young adult male driver of a passenger car in a single-vehicle crash (4.6%). The highest probabilities of fatality were associated with older adult male drivers in head-on collisions, for trucks (3.4% probability) and passenger cars (3.2% probability). Again, manner of crash emerged as a differentiating risk factor, with head-on collisions exceeding 2% probability of fatality and single-vehicle collisions exceeding 1% probability of fatality across other variable combinations. For each vehicle type (Figs. A4, A6, A8), matching person demographics within manner of crash where possible, general trends again observed a slightly elevated fatality risk for males over females, and with increasing age. For example, in passenger cars (Fig. A4), the risk of fatality in an angle crash was elevated for males over females by 0.2% in young adults and 0.3% in middle-aged and older adults. The risk of fatality in a single vehicle crash also increased for males over females by 0.4% in young adults and 0.5% in middle-aged and older adults. Similarly, in MPVs in single vehicle crashes (Fig. A6), the probability of fatality for males exceeded females by 0.3% in young adults and 0.4% in middle-aged and older adults.

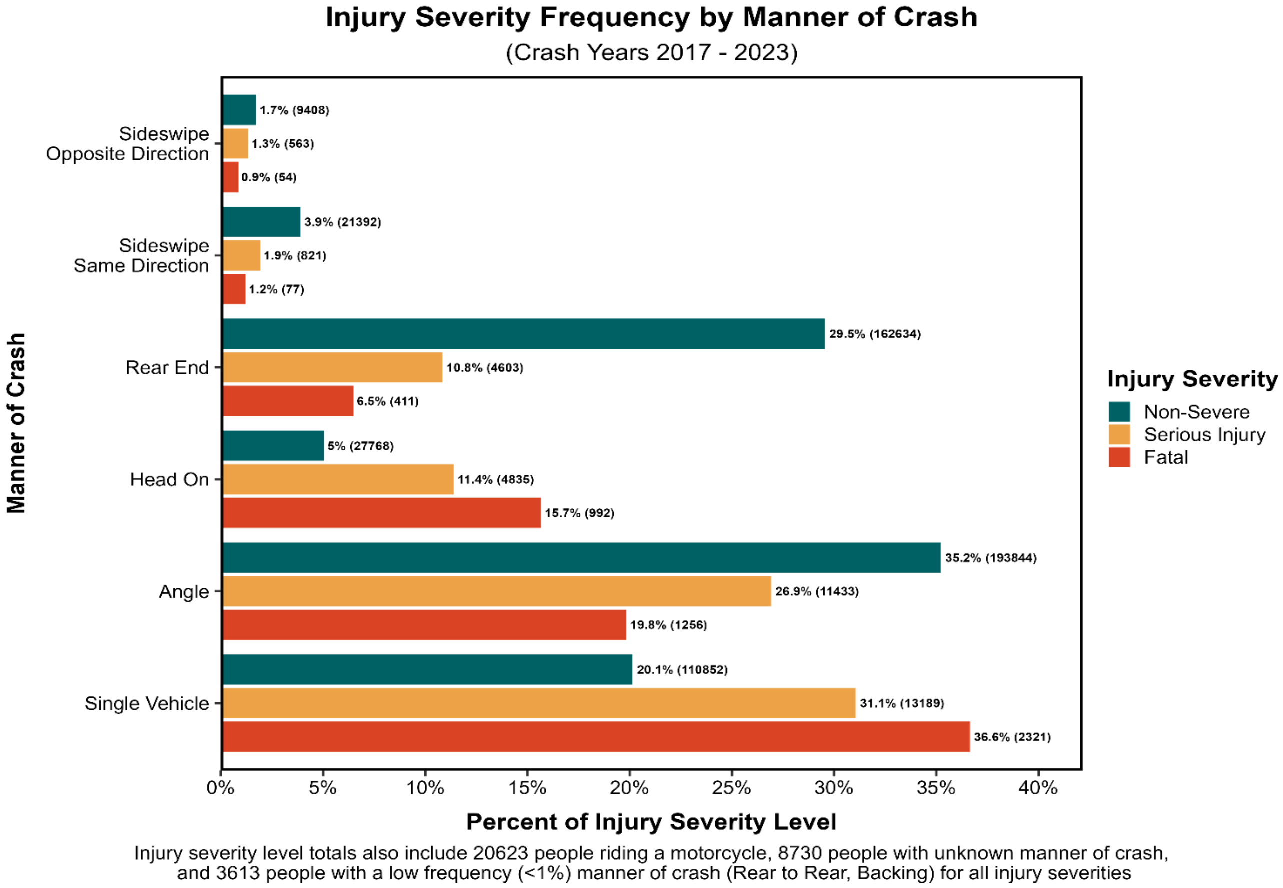

Fig. 1. Fraction of total non-severe, suspected serious, and fatal injuries contributed by each manner of crash

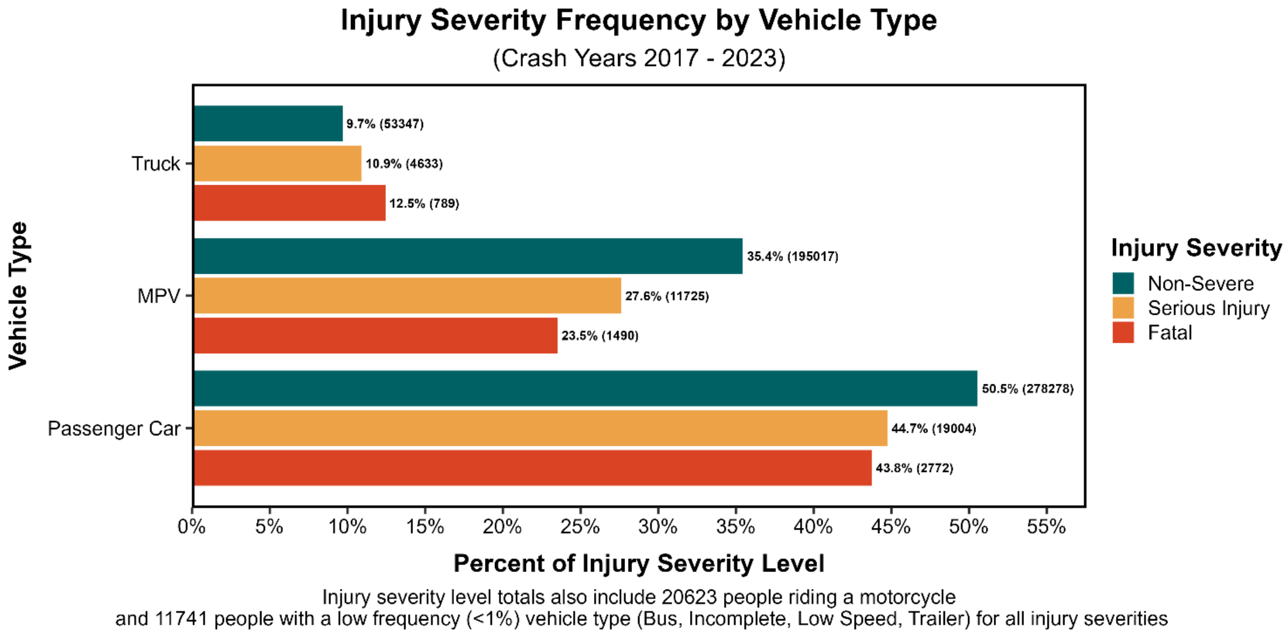

Fig. 2. Fraction of total non-severe, suspected serious, and fatal injuries contributed by each vehicle type

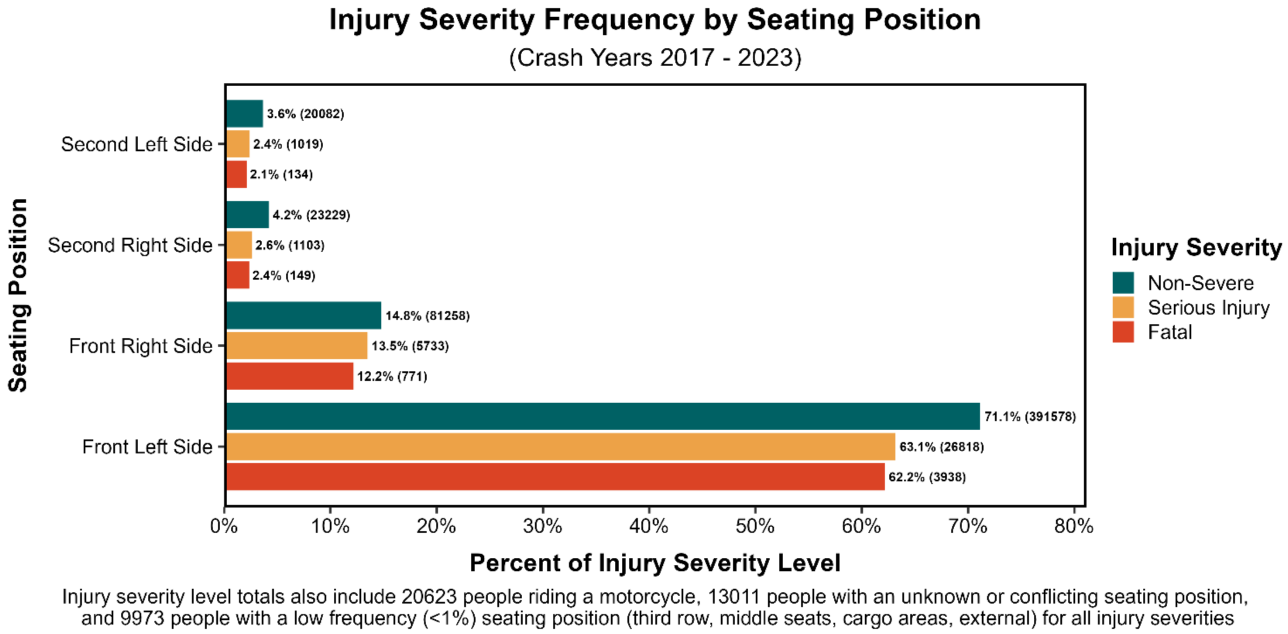

Fig. 3. Fraction of total non-severe, suspected serious, and fatal injuries contributed by each seating position

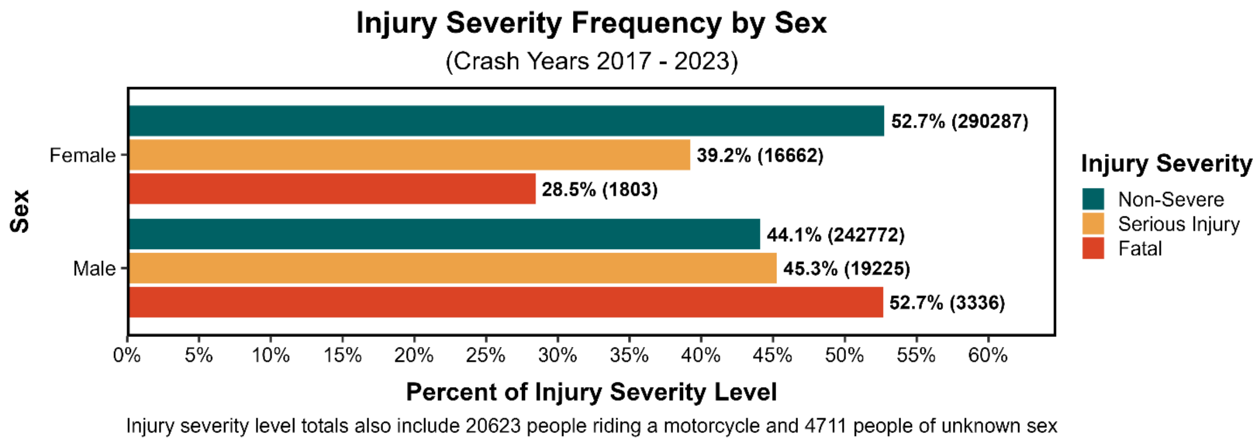

Fig. 4. Fraction of total non-severe, suspected serious, and fatal injuries contributed by each sex

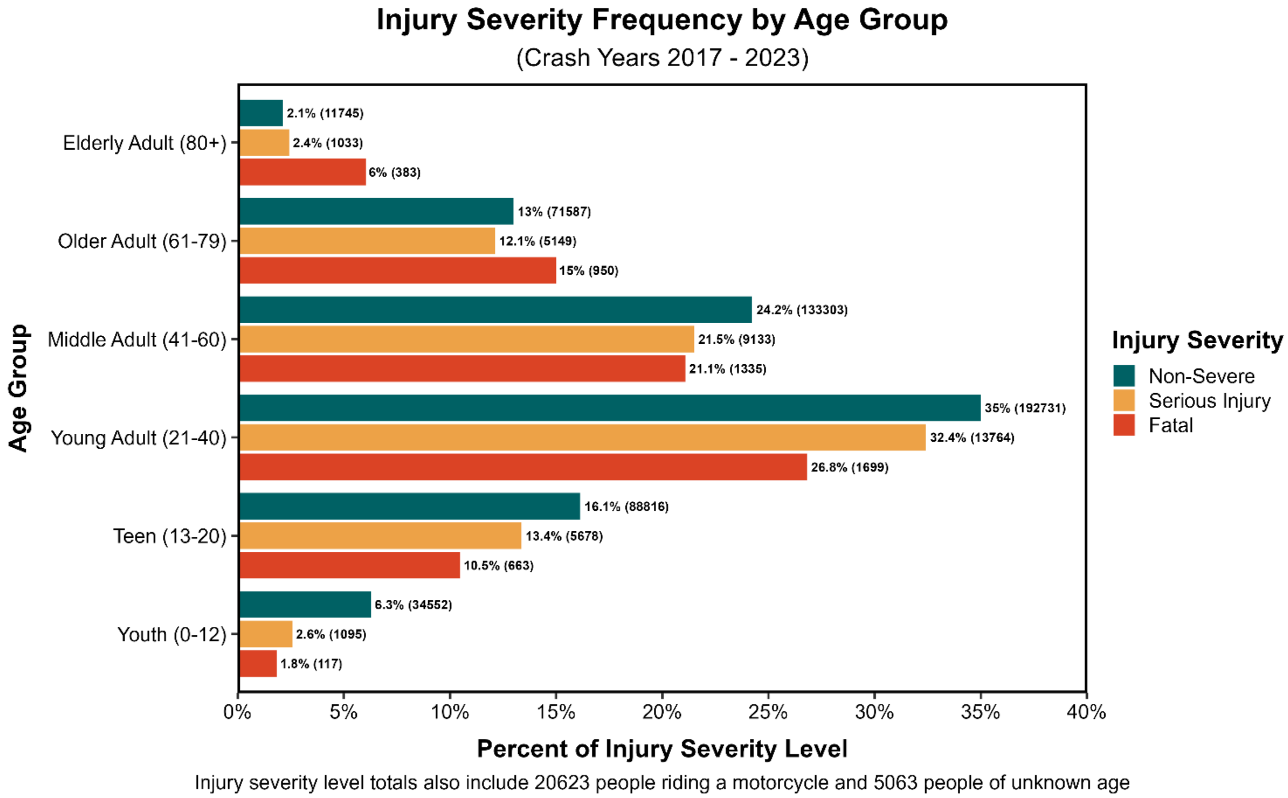

Fig. 5. Fraction of total non-severe, suspected serious, and fatal injuries contributed by each age group

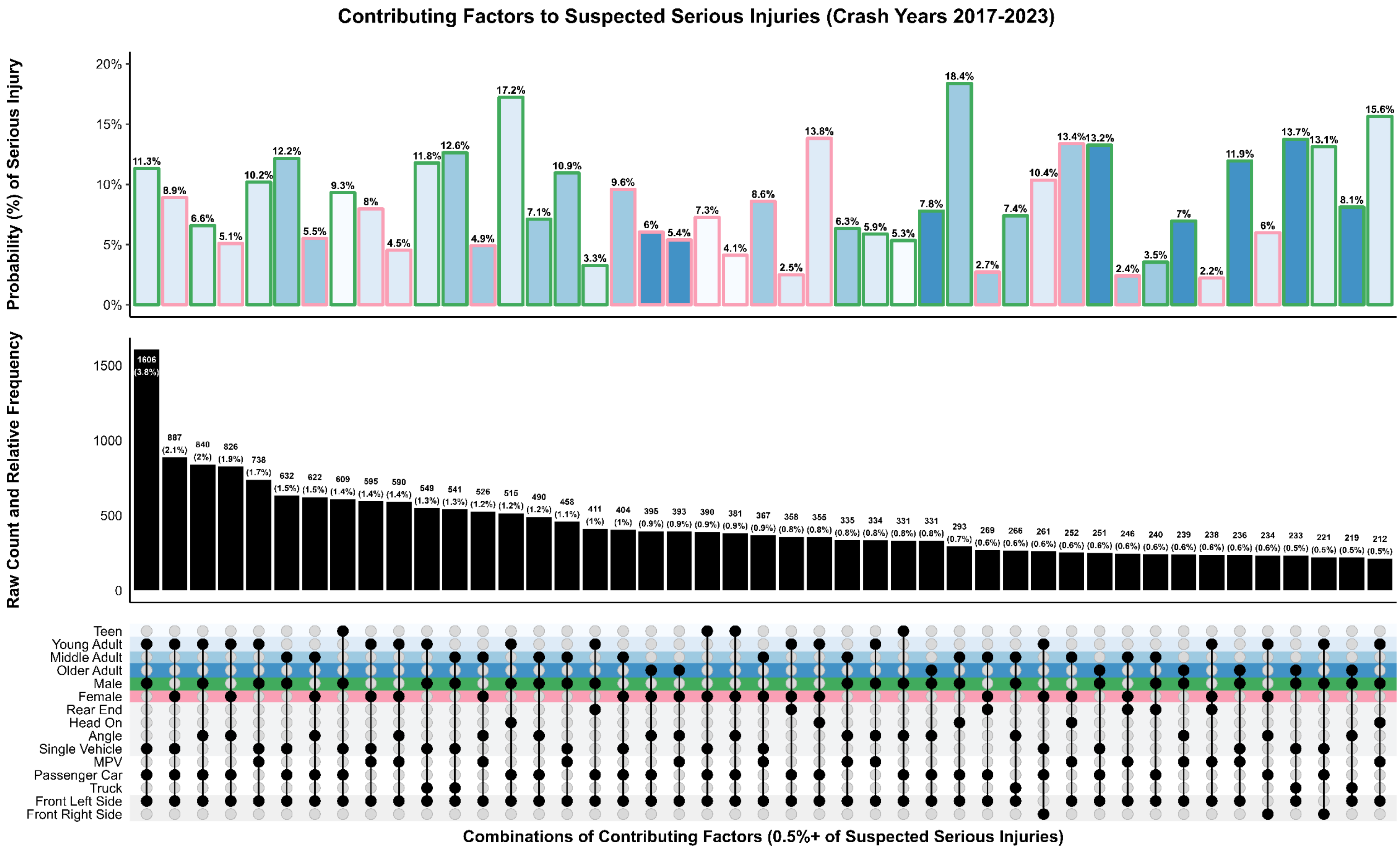

Fig. 6. Upset plot of suspected serious injuries across all vehicle types (Passenger Cars, MPVs, Trucks), as associated with person and vehicle variables (black dots) and their intersections (black lines). Black bars show the count and relative frequency (percentage) of the variable combination within all suspected serious injuries. Colored bars show the predicted probability of suspected serious injury, with the outline color indicating sex, and the fill indicating age group.

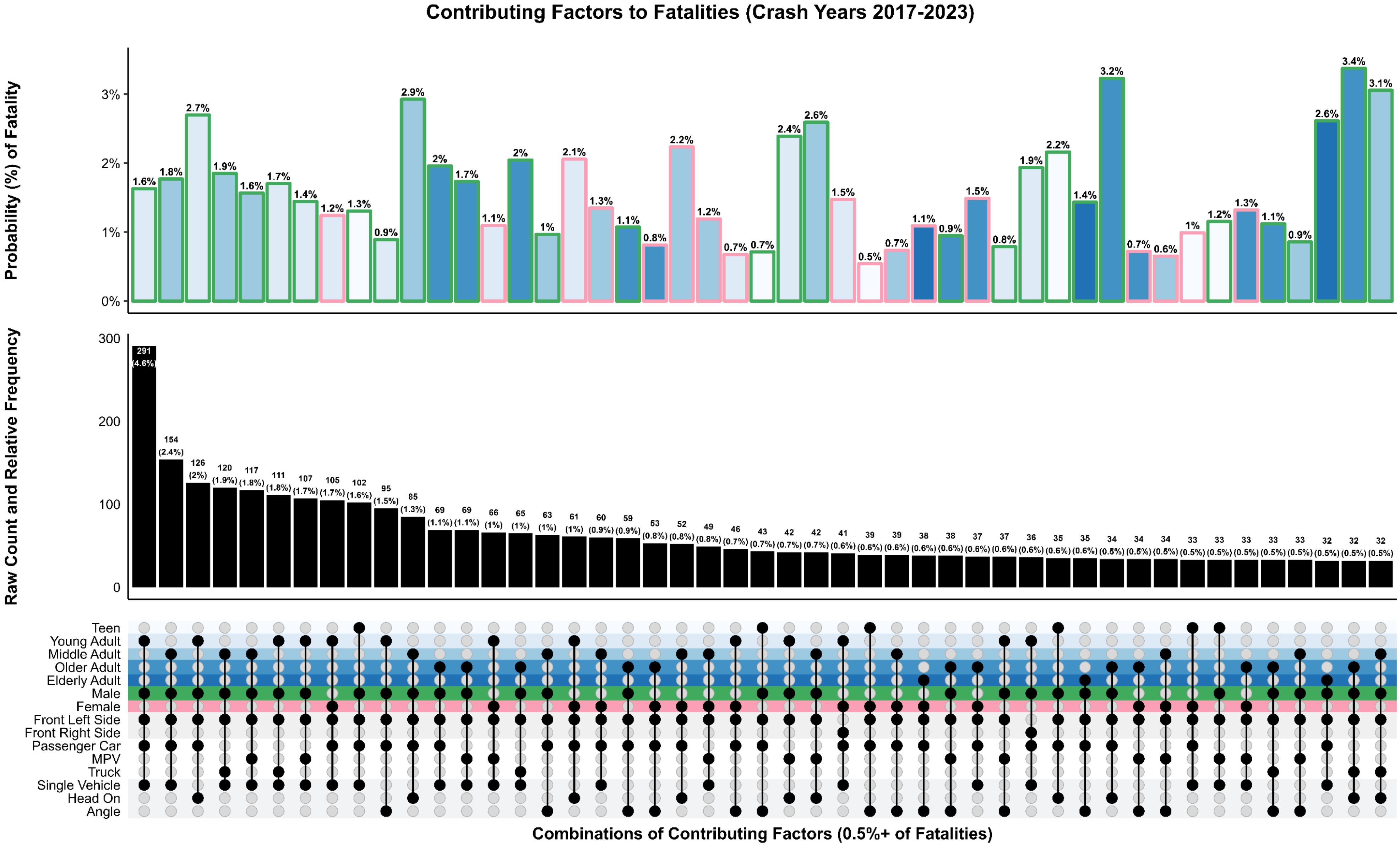

Fig. 7. Upset plot of fatalities across all vehicle types (Passenger Cars, MPVs, Trucks), as associated with person and vehicle variables (black dots) and their intersections (black lines). Black bars show the count and relative frequency (percentage) of the variable combination within all fatalities. Colored bars show the predicted probability of fatality, with the outline color indicating sex, and the fill indicating age group.

Analysis of BMI and Its Relationship with Age and Sex in MVC Fatalities

Sub-sample analyses of autopsy data identified obesity as the most frequent BMI category among motor vehicle crash fatalities, these data include any individual involved in a MVC, including pedestrians, bicyclists, and other VRUs (Fig. 8). Obesity exhibited the highest distribution of fatalities across multiple age and sex groups (Fig. A9), underscoring the need for targeted interventions. Importantly, the dataset includes individuals across the full range of BMI categories, and the sample is not skewed or restricted to obese individuals. When compared to the overall prevalence of obesity in Ohio (35.5%) [31], the proportion of individuals classified as obese among crash fatalities (42.1%) is notably overrepresented. This indicates that the elevated fatality rates among obese individuals are not merely a reflection of underlying population demographics but point to a disproportionate risk that warrants focused attention in injury prevention strategies. Further, the intersection of age and sex with BMI (Fig. A9) found that obese males account for the highest fraction of fatalities (28.4%), concentrated in the middle (10.3%) and young adult (9.0%) groups.

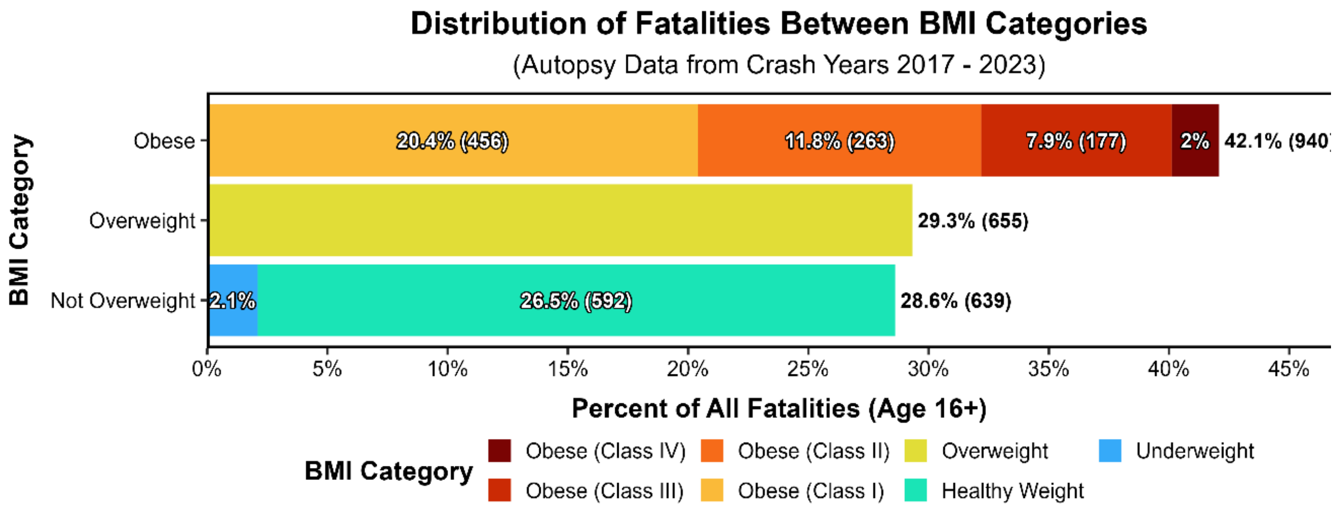

Fig. 8. Distribution of fatalities between BMI categories

IV. DISCUSSION

This retrospective analysis of Ohio crash data highlights key patterns in occupant vulnerability, emphasizing the role of manner of crash, vehicle type, seating position, and demographic information in non-severe, suspected serious, and fatal injury levels. Overall, non-severe injuries were the most common outcome, comprising the majority of reported injuries, while suspected serious injuries and fatalities accounted for smaller proportions, but with notable differences in injury severity across various categories, including the manner of crash, vehicle type, seating position, and occupant demographics.

Single-vehicle and angle crashes demonstrated the highest frequencies of both serious suspected injuries and fatalities (Fig. 3, Table AV). This finding is partially supported by [13], which used the National Automotive Sampling System Crash Worthiness Data System to examine injuries patterns in rear seat passengers. They identified single-vehicle crashes as the leading manner of crash for serious injuries and fatalities. However, while the current study found angle collisions to be the most prevalent in multiple-vehicle crashes (Fig. 3, Table AV), [13] reported head-on crashes as the leading type. Additionally, [32] observed a divergence from these findings, with the most common manner of crash was with another vehicle. These discrepancies may reflect variations in crash trends due to factors such as locale, sample characteristics, seating position, and other contextual elements. While single-vehicle and angle crashes contribute the most to the overall count of serious injuries and fatalities in the current study, head-on crashes, though less frequent, generally have the highest probability of suspected serious injuries or fatalities.

While passenger cars were the most frequently involved vehicle type for both suspected serious injuries and fatalities, the frequency of MPVs and trucks differed between these injury categories (Fig. 4, Table AVI). While these data represent the frequency of these types of vehicles on the road, when analyzed individually, different patterns in frequency combinations with other variables and the predicted probability of injury demonstrate more distinct outcomes between the vehicle types (Figs. A3–A8). In the passenger car only analysis, the highest predicted probability of a suspected serious injury involved the combined factors of male, middle adult, driver, in a head-on crash (18.4%) (Fig. A3). Similar to the suspected serious injuries, the highest predicted probability of fatality within passenger cars only consisted of the same variables with an exception in age, where age shifted to older adult (3.2%) (Fig. A4). When MPVs were analyzed as a distinct category, the highest predicted probability of suspected serious injury was the combination of male, young adult, driver, in a head-on crash (15.6%) (Fig. A5). As demonstrated in passenger cars, the MPV only analysis of the predicted probability of fatality differed from suspected serious injuries in the age category only, again shifting to older adult (2.9%) (Fig. A6). Results of the truck only analyses deviate from the patterns observed in passenger car and MPV analyses, because head-on crashes did not have a high enough frequency (0.5% of all suspected serious injuries) within any demographic configuration. The highest predicted probability of suspected serious injury in trucks was observed in the variable combination of male, older adult, driver, single-vehicle crash (13.7%) (Fig. A7). For fatalities, the highest predicted probability was again a male, older adult, driver, head-on crash (3.4%) (Fig. A8). These findings highlight that while frequency patterns for vehicle types like passenger cars, MPVs, and trucks are influenced by overall road presence, the predicted probabilities of injury severity are more strongly determined by specific variable combinations, such as crash type, age, and sex, which vary notably across vehicle categories. These results underscore the need for targeted prevention strategies that address the unique risks associated with different vehicle types and crash scenarios.

While this study focused on the types of collisions and the overall risk of injury across different vehicle types, it is important to note that vehicle type crash compatibility was not specifically analyzed in this context. The interaction between different vehicle types in crashes, particularly regarding differences in size, structure, and crashworthiness, will be incorporated into future studies. Vehicle compatibility, especially in crashes between passenger cars and larger vehicles like trucks or MPVs, plays a significant role in injury outcomes, as these vehicles have different crash dynamics and occupant protection features [37]. Future research will examine how these factors contribute to varying injury severity in mixed-vehicle crashes.

The results of this study indicate that seating position may be an important contributor to occupant vulnerability, with drivers disproportionately represented in injury and fatality statistics (Fig. 5, Table AIV). The front passenger seat accounted for a smaller, yet notable proportion of injuries (14.8% non-severe, 13.5% serious, and 12.2% fatal), suggesting that existing vehicle safety features offer a relatively high degree of protection. Conversely, rear-seat occupants exhibited lower injury rates, although this may be partially attributable to lower occupancy rates rather than an inherent increase in safety. The seating position of driver (front left) as overrepresented in injuries and fatalities are consistent with the studies of [6][32][34]. However, they contrast with the conclusions of [33][38–39] who reported higher or comparable injury frequencies for front seat passengers. The impact of seating position is skewed due to the consistent presence of a driver in all vehicles, making it difficult to conclusively determine whether any specific seating position is inherently safer than others. The current study, therefore, cannot definitively assert the relative safety of different seating positions. These findings highlight the necessity of ensuring that restraint systems provide adequate protection for all seating positions. Future work will include more direct comparisons of seating positions beyond the driver to provide a clearer understanding of the relative risks associated with each position.

This study also sheds light on the importance of occupant demographics on vulnerability, finding that sex, age, and BMI were all associated with prevalence of injury and fatality. Injury frequency by age group reveals distinct trends that emphasize the varying vulnerability across different age groups of occupants (Figs. 7, A2). Young adults (ages 21–40) exhibited the highest occurrence of injury in all categories, suggesting that young adults are particularly susceptible to higher injury severity, possibly due to factors such as riskier driving behaviors, inexperience, or higher exposure to traffic. Middle-aged adults (ages 41–60) followed, showing that while they are less vulnerable than younger adults, they still experience a significant proportion of injuries and fatalities (Fig. 7, Table AIII). A notable decline in injury frequency was observed in both older adults (ages 61–79) and teens (ages 12–20), as well as among elderly adults (ages 80+) and youths (ages 0–12). This decrease may be partially explained by the reduced numbers of older and younger individuals on the road, as they generally have lower road user exposure compared to working-age adults, who are more likely to be daily commuters.

Furthermore, the decline in injury frequency with age does not necessarily indicate greater safety for older adults, as when crashes do occur, the likelihood of serious or fatal outcomes increases. This highlights the complex relationship between age and injury severity, where age alone does not fully account for risk. These trends underscore the need for targeted interventions such as enhanced driver education programs for younger populations and the implementation of adaptive safety features to protect older drivers, especially in light of the heightened risk of severe injury in crashes involving older adults.

Additionally, this study found that young male drivers are disproportionately involved in serious and fatal crashes, a pattern consistent with previous research, including studies by [6–7][11][16][36]. These studies report higher injury rates among younger age groups, with the upper age limit ranging from 25 to 39 depending on the study. Notably, [7] highlighted that individuals aged 65+ experience higher injury rates, although this trend was not observed in the current study. However, while older individuals in this study were found to be less frequently involved in injurious crashes, they have a slightly elevated risk for suspected serious injuries and fatalities. The vulnerability of older populations is supported by additional research, which highlights the increased crash and injury risk for older individuals [12–15][32][40]. Some studies suggest that the injury risk for older individuals can double or triple compared to that of 20-year-olds [32][40]. Moreover, research by [7][32] indicates that the relationship between age and injury frequency does not follow a simple linear trend but rather forms a curve, with both younger and older individuals facing higher injury risks than those in middle age. This complex relationship is further supported by [41], who found that while young drivers were more frequently involved in crashes, overall fatality rates decreased as the elderly population increased.

The relationship between sex and injury is complex, with some studies supporting the current findings of male overrepresentation in injuries [6][16][36]. However, other research indicates higher injury or fatality risks for female occupants [13] or an equal distribution of risk between sexes [14]. Examining interactions between sex, crash characteristics, and injury further complicates vulnerability patterns. Studies show that factors such as age and the manner of crash impact the distribution of injury or fatality between sexes [32][36][38][40]. For example, [32] found that in collisions with other motor vehicles, males and females were equally represented in injuries and hospitalizations, whereas in loss-of-control crashes, males were overrepresented. These discrepancies in the role of sex and age in crash and injury severity highlight the need for further investigation, as they may reflect temporal or regional trends in demographic data for crash-related injuries.

Investigating BMI, this study found that individuals classified as obese (BMI ≥ 30) are more frequently involved in fatal crashes than other BMI categories (Fig. 6). This finding aligns with previous research [13][34], both of which reported statistically significant increases in injury frequency and risk among overweight and obese individuals. In the current study, fatalities with a BMI classification of obese were higher than general Ohio population rates [31], indicating that obese individuals are overrepresented in crash fatalities. This overrepresentation is not solely attributable to population demographics but may also be related to health factors or the compatibility of vehicle safety features with higher body mass. Additionally, the study found that middle-aged (ages 41–60) and young adult (ages 21–40) males in higher BMI categories demonstrated higher frequencies of fatalities, suggesting that vehicle restraint systems may not adequately accommodate individuals with larger body types (Fig. A9). These findings underscore the need for improved restraint system designs to better accommodate a broader range of body types and call for further research into the relationship between obesity and crash outcomes. Overall, this study emphasizes the intersection of crash, vehicle, and demographic factors such as sex, age, and BMI in influencing injury vulnerability, highlighting the importance of addressing these factors in vehicle safety design and public health interventions.

V. CONCLUSION

This study applies a comprehensive conceptual framework, informed by the SSA, to assess occupant vulnerability in vehicular crashes by integrating situational, vehicle, and demographic factors. By combining demographic data with regional crash analysis, it offers valuable insights into context-dependent vulnerability patterns, emphasizing the need for region-specific safety strategies and policy interventions. The analysis of Ohio crash data highlights key trends, such as the elevated frequency of suspected serious injury and fatality in single-vehicle and angle collisions. Head-on crashes, although less prevalent, tend to have the highest probability of suspected serious injury or fatality. Demographic factors, including age, sex, and BMI, have relationships with the frequencies of various injury severity levels, underlining the importance of targeting high-risk groups in safety interventions.

Males, young adults (20–29), and obese individuals were identified as particularly vulnerable, with passenger cars and drivers being predominantly involved in serious injuries and fatalities. Regional data from Ohio underscores the necessity of localized insights for informing both state and national safety policies. This study calls for enhanced vehicle safety measures, tailored education campaigns, and region-specific interventions to address the unique risk factors present in different areas. The findings also have broader applicability beyond Ohio, as many of the identified risk factors are relevant across various regions. Future research should extend these analyses to further refine global occupant safety strategies. Ultimately, this research highlights the need for targeted safety interventions, including crash avoidance technologies and improved occupant protection systems, to ensure adequate protection for all vehicle occupants, regardless of demographic or geographic differences.

VI. ACKNOWLEDGEMENTS

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VIII. APPENDIX

TABLE AI
BODY MASS INDEX (BMI) CATEGORIES

BMI Category	Adults (Age 20+)	Teens (Ages 16–19)
Underweight	< 18.5 kg/m^2	< 5th percentile
Healthy Weight	18.5 to 24.9 kg/m^2	5th to 84th percentile
Overweight	25 to 29.9 kg/m^2	85th to 94th percentile
Obese Class I	30 to 34.9 kg/m^2	95th to 119th percentile
Obese Class II	35 to 39.9 kg/m^2	120th to 139th percentile
Obese Class III	40 to 49.9 kg/m^2	≥ 140th percentile
Obese Class IV	≥ 50 kg/m^2	NA

TABLE AII
CRASH, VEHICLE, DEMOGRAPHIC, AND INJURY SEVERITY VARIABLE DEFINITIONS

Category	Variable	Definition
Manner of Crash	Single-Vehicle	Unless there are at least two motor vehicles in transport involved, the manner of crash is Not Collision Between Two Motor Vehicles (further referred to as Single-Vehicle)
	Angle	When vehicles are traveling in perpendicular directions
	Head-On	Vehicles must be traveling in opposite directions and the majority of the impact is the front area of both units
	Rear-End	Vehicle must be traveling in the same direction
	Sideswipe Same Direction	When vehicles are traveling in the same direction and the majority of the damage is related to the sides of the units
	Sideswipe Opposite Direction	When vehicles are traveling in opposite directions and the majority of the damage is related to the sides of the units
Vehicle Type	Passenger Car	Any motor vehicle that (1) has motive power, (2) is designed to carry 10 persons or less (including the driver), and (3) that is not a multipurpose passenger vehicle, motorcycle, or trailer
	Multipurpose Passenger Vehicle	A motor vehicle with motive power, except a trailer, designed to carry 10 people or less which is constructed either on a truck chassis or with special features for occasional off-road operation
	Truck	A motor vehicle with motive power, except a trailer, designed primarily for the transportation of property or special purpose equipment
Seating Position	Front Left Side Front Right Side Second Left Side Second Right Side	The motorist/occupant's location in, on, or outside of the vehicle prior to the crash
Demographics	Sex	The motorist/occupant's gender limited to Female, Male, or Unknown/Other
	Age	Age reported on the traffic crash report and validated by birthdate
	Body Mass Index (BMI)	Measure of weight relative to height
Injury Severity	Non-Severe	Combined category of both Possible Injury (Any injury recorded or claimed which is not a fatal, serious injury, or minor injury. Possible injuries are those that are reported by the person or are indicated by his/her behavior, but no wound or injuries are readily evident) and Suspected Minor Injury (Any injury that is evident at the scene of the crash, other than fatal or suspected serious injuries)
	Suspected Serious Injury	Any injury other than fatal which results in one or more of the following: Severe laceration resulting in exposure of underlying tissues/muscle/organs, or resulting in significant loss of blood, broken or distorted extremity (arm or leg), crush injuries suspected skull, chest or abdominal injury other than bruises or minor lacerations, significant burns (second and third degree burns over 10% or more of the body) unconsciousness when taken from the crash scene, or paralysis
	Fatal	Any injury that results in death within 30 days after the motor vehicle crash in which the injury occurred

TABLE AIII

DESCRIPTIVE STATISTICS OF DEMOGRAPHIC VARIABLES IN FULL DATASET

Group	Variable	Non-Severe Injuries (n)	Non-Severe Injuries (%)	Suspected Serious Injuries (n)	Suspected Serious Injuries (%)	Fatalities (n)	Fatalities (%)
Sex	Female	290,287	52.7	16,662	39.2	1,803	28.5
	Male	242,772	44.1	19,225	45.3	3,336	52.7
Age	0-8	23,702	4.3	696	1.6	82	1.3
	9–13	13,549	2.5	522	1.2	46	0.7
	14–19	58,856	10.7	3,723	8.8	446	7.0
	20–29	121,088	22.0	8.535	20.1	991	15.6
	30–39	91,088	16.5	6,526	15.4	845	13.3
	40–49	69,215	12.6	4,835	11.4	703	11.1
	50–59	65,632	11.9	4,394	10.3	638	10.1
	60–69	50,424	9.2	3,498	8.2	544	8.6
	70–79	27,425	5.0	2,090	4.9	470	7.4
	80–89	10,230	1.9	902	2.1	318	5.0
	90+	1,515	0.3	131	0.3	65	1.0

Injury severity level totals used to calculate percentages also include 20,623 people riding a motorcycle, 4,711 people of unknown sex, and 5,063 people of unknown age.

TABLE AIV
DESCRIPTIVE STATISTICS OF SEATING POSITION AND INJURY LEVELS IN FULL DATASET

Group	Variable	Non-Severe Injuries (n)	Non-Severe Injuries (%)	Suspected Serious Injuries (n)	Suspected Serious Injuries (%)	Fatalities (n)	Fatalities (%)
Seating Position	Front Left Side	391,578	71.1	26,818	63.1	3,938	62.2
	Front Middle	830	0.2	69	0.2	6	0.1
	Front Right Side	81,258	14.8	5,733	13.5	771	12.2
	Second Left Side	20,082	3.6	1,019	2.4	134	2.1
	Second Middle	4,781	0.9	288	0.7	26	0.4
	Second Right Side	23,229	4.2	1,103	2.6	149	2.4
	Third Left Side	1,383	0.3	61	0.1	5	0.1
	Third Middle	531	0.1	30	0.1	3	0.05
	Third Right Side	1,283	0.2	59	0.1	1	0.02
	Trailing Unit	6	0.001	3	0.01	0	0
	Sleeper Section of Truck Cab	139	0.03	17	0.04	3	0.05
	Passenger in Other Enclosed Cargo Area	331	0.1	11	0.03	1	0.02
	Passenger in Unenclosed Cargo Area	27	0.005	8	0.02	5	0.1
	Riding on Vehicle Exterior	36	0.01	28	0.1	2	0.03

Injury severity level totals used to calculate percentages also include 20,623 people riding a motorcycle and 12,011 people with an unknown or conflicting seating position.

TABLE AV
DESCRIPTIVE STATISTICS OF MANNER OF CRASH AND INJURY LEVELS IN FULL DATASET

Group	Variable	Non-Severe Injuries (n)	Non-Severe Injuries (%)	Suspected Serious Injuries (n)	Suspected Serious Injuries (%)	Fatalities (n)	Fatalities (%)
Manner of Crash	Single-Vehicle	110,852	20.1	13,189	31.1	2,321	36.6
	Angle	193,844	35.2	11,433	26.9	1,256	19.8
	Head-On	27,768	5.0	4,835	11.4	992	15.7
	Rear-End	162,634	29.5	4,603	10.8	411	6.5
	Sideswipe Same Direction	21,392	3.9	821	1.9	77	1.2
	Sideswipe Opposite Direction	9,408	1.7	563	1.3	54	0.9
	Backing	2,147	0.4	31	0.1	3	0.05
	Rear to Rear	1,391	0.3	40	0.1	1	0.02

Injury severity level totals used to calculate percentages also include 20,623 people riding a motorcycle and 8,730 people with an unknown manner of crash.

TABLE AVI
DESCRIPTIVE STATISTICS OF VEHICLE TYPE AND INJURY LEVELS IN FULL DATASET

Group	Variable	Non-Severe Injuries (n)	Non-Severe Injuries (%)	Suspected Serious Injuries (n)	Suspected Serious Injuries (%)	Fatalities (n)	Fatalities (%)
Vehicle Type	Passenger Car	278,278	50.5	19,004	44.7	2,772	43.8
	Multipurpose Passenger Vehicle (MPV)	195,017	35.4	11,725	27.6	1,490	23.5
	Truck	53,347	9.7	4,633	10.9	789	12.5
	Motorcycle	13,033	2.4	6,408	15.1	1,182	18.7
	Bus	3,916	0.7	126	0.3	17	0.3
	Incomplete Vehicle	6,952	1.3	566	1.3	84	1.3
	Trailer	69	0.01	6	0.01	0	0
	Low Speed Vehicle (LSV)	4	0.001	1	0.002	0	0

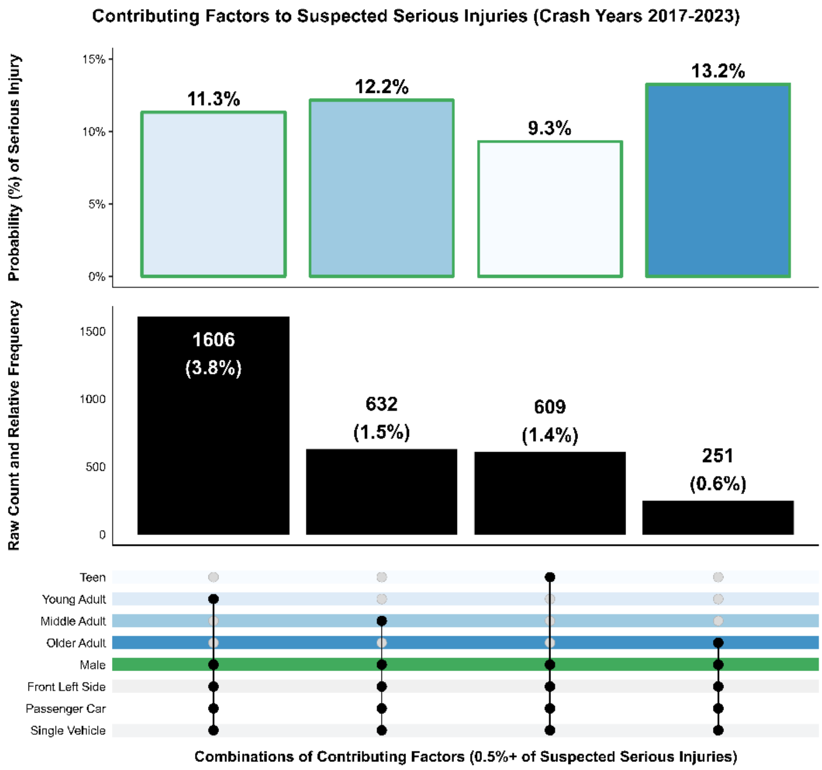

Fig. A1. Upset plot of suspected serious injuries, abridged to show only variation in age group for male drivers of passenger cars in single vehicle crashes. Black bars show the raw suspected serious injury count of each variable combination, and its relative frequency (percentage) of all suspected serious injuries. Colored bars show the predicted probability of suspected serious injury for each variable combination, with the bar outline color indicating sex, and the bar fill indicating age group.

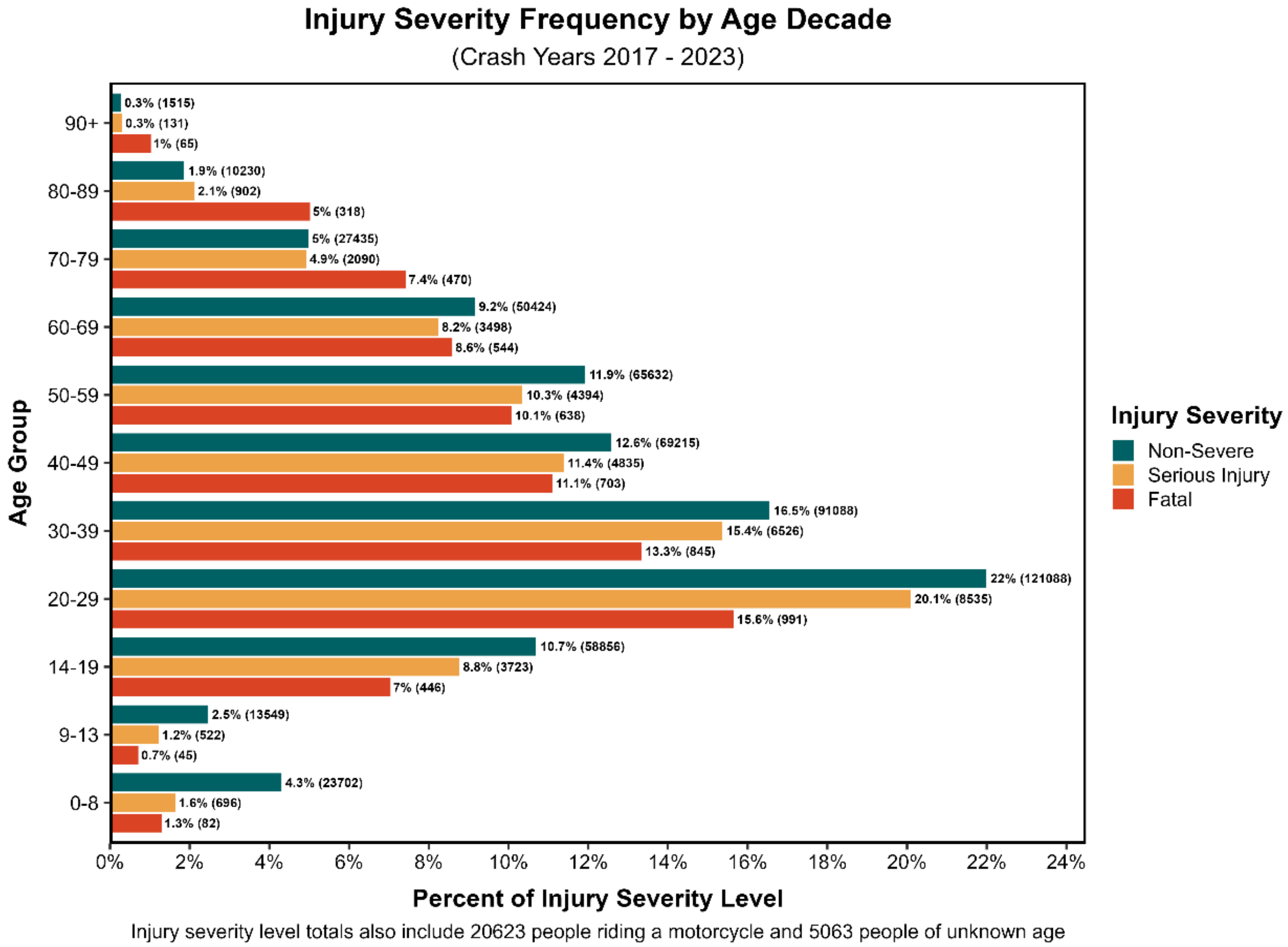

Fig. A2. Percentage of all non-severe, serious, and fatal injuries associated with age decade

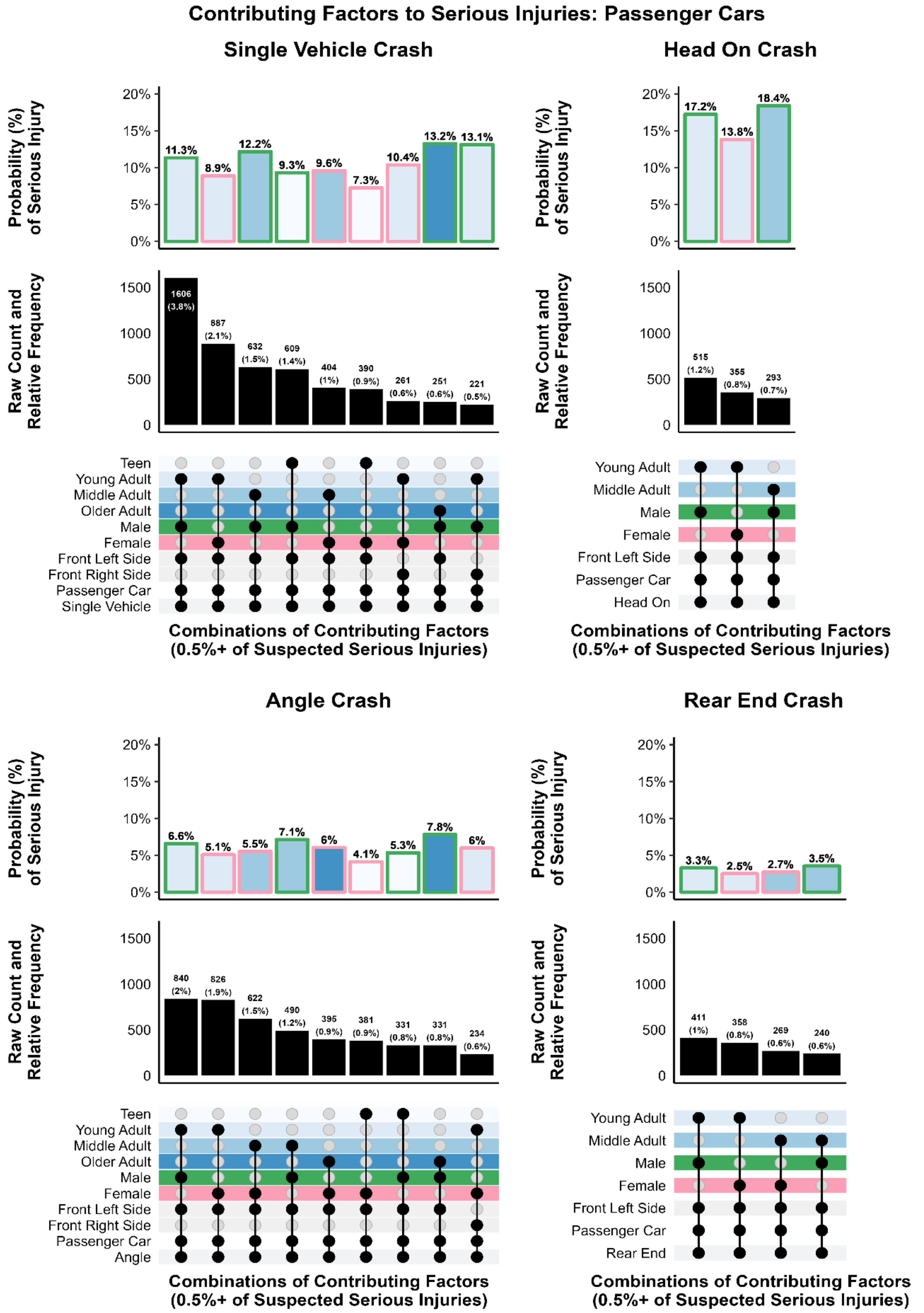

Fig A3. Upset plot of suspected serious injuries within Passenger Cars, as associated with person and vehicle variables (black dots) and their intersections (black lines). Variable combinations are displayed if they represent at least 0.5% of all suspected serious injuries. Black bars show the raw suspected serious injury count of each variable combination, and its relative frequency (percentage) of all suspected serious injuries. Colored bars show the predicted probability of suspected serious injury for each variable combination, with the bar outline color indicating sex, and the bar fill indicating age group.

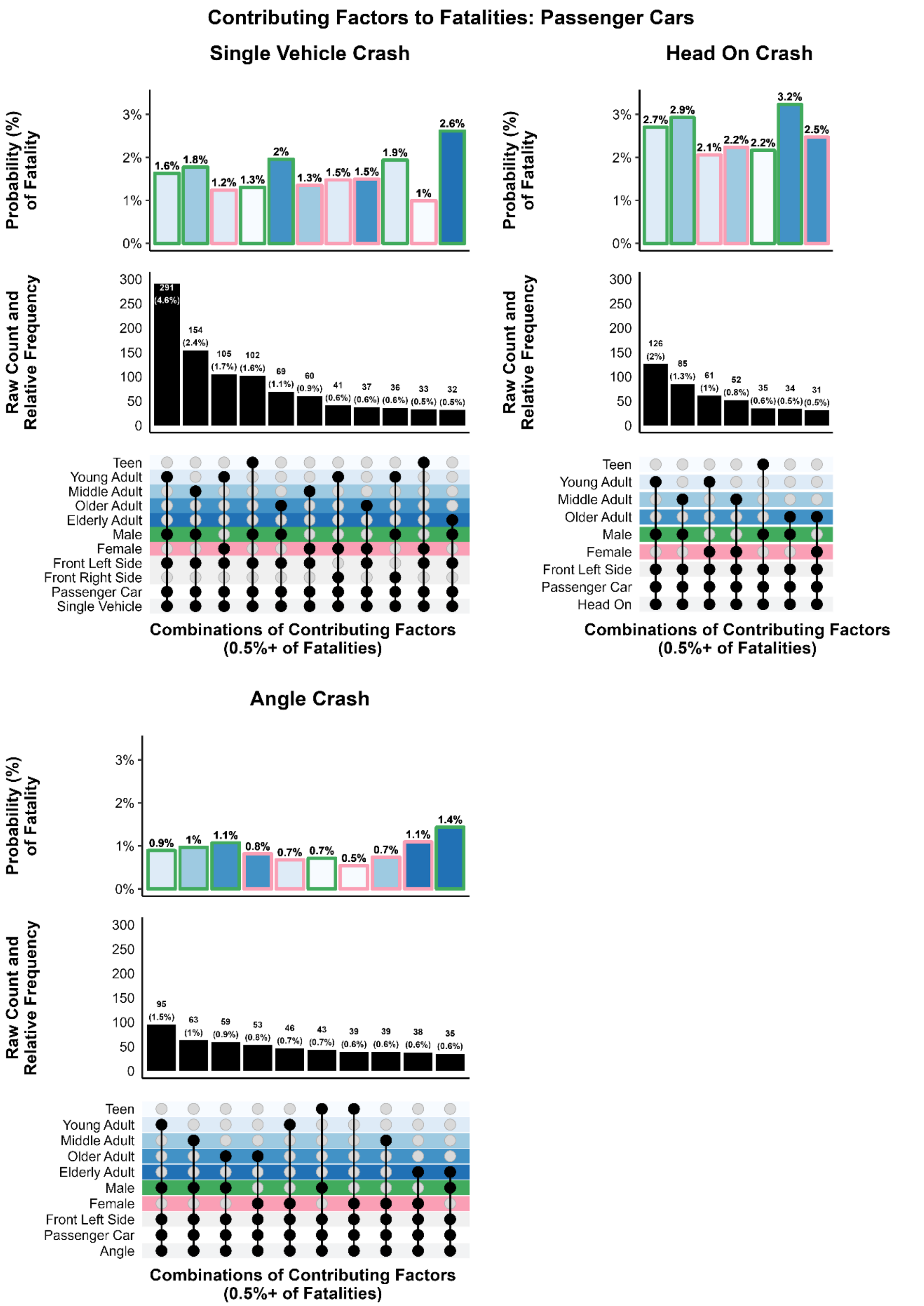

Fig. A4. Upset plot of fatalities within Passenger Cars, as associated with person and vehicle variables (black dots) and their intersections (black lines). Variable combinations are displayed if they represent at least 0.5% of all fatalities. Black bars show the raw fatality count of each variable combination, and its relative frequency (percentage) of all fatalities. Colored bars show the predicted probability of fatality for each variable combination, with the bar outline color indicating sex, and the bar fill indicating age group.

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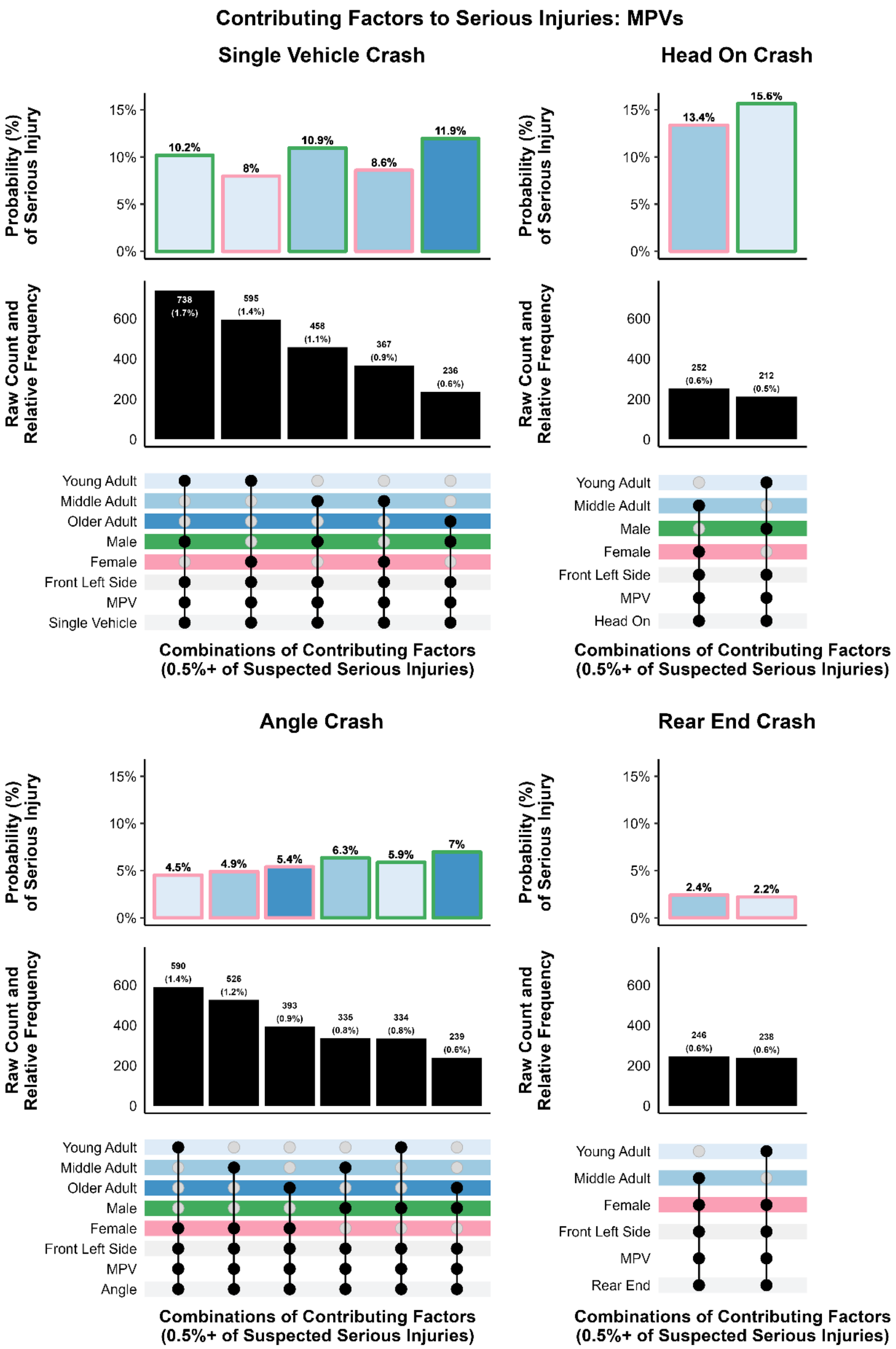

Fig A5. Upset plot of suspected serious injuries within MPVs, as associated with person and vehicle variables (black dots) and their intersections (black lines). Variable combinations are displayed if they represent at least 0.5% of all suspected serious injuries. Black bars show the raw suspected serious injury count of each variable combination, and its relative frequency (percentage) of all suspected serious injuries. Colored bars show the predicted probability of suspected serious injury for each variable combination, with the bar outline color indicating sex, and the bar fill indicating age group.

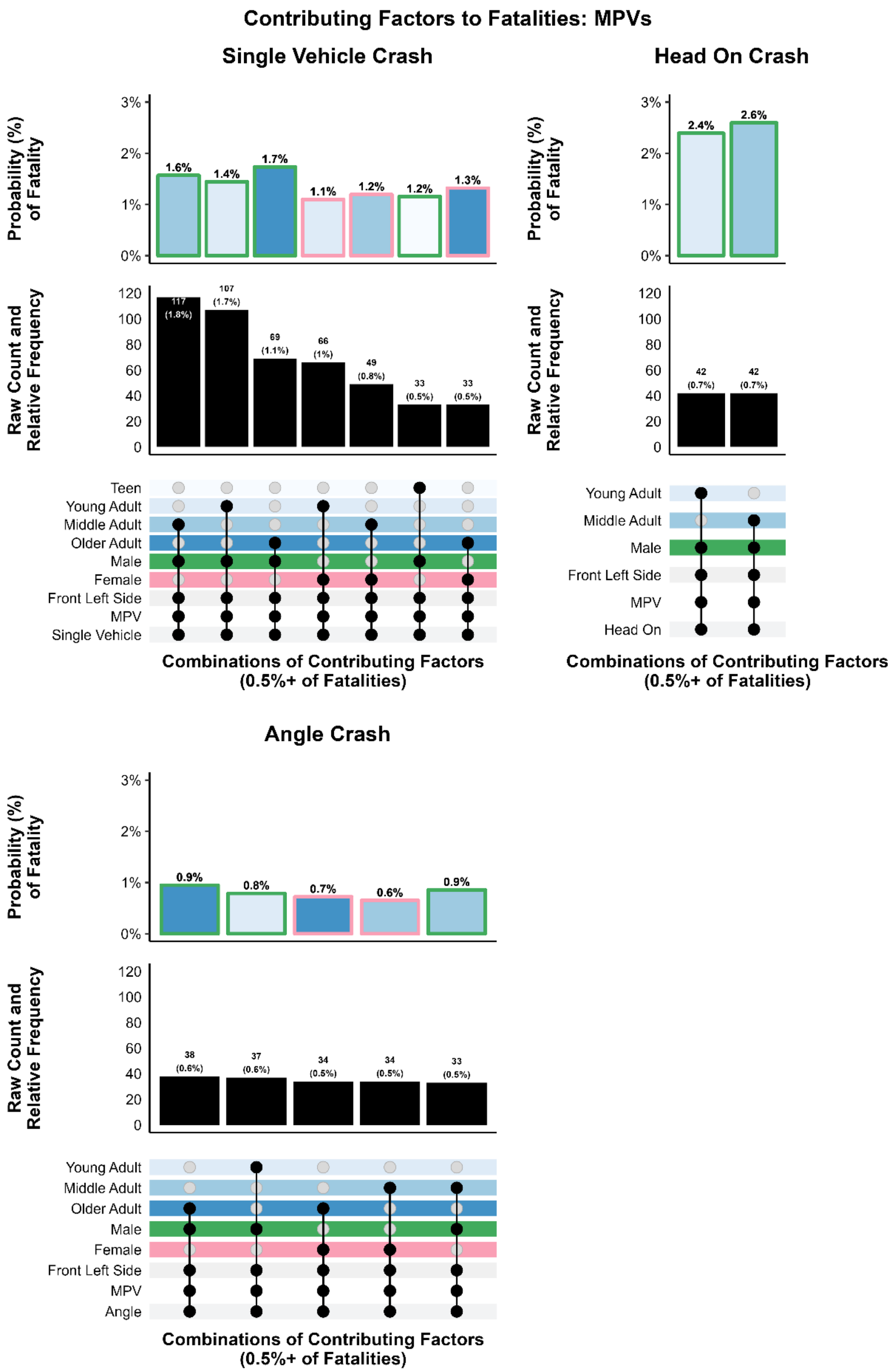

Fig A6. Upset plot of fatalities within MPVs, as associated with person and vehicle variables (black dots) and their intersections (black lines). Variable combinations are displayed if they represent at least 0.5% of all fatalities. Black bars show the raw fatality count of each variable combination, and its relative frequency (percentage) of all fatalities. Colored bars show the predicted probability of fatality for each variable combination, with the bar outline color indicating sex, and the bar fill indicating age group.

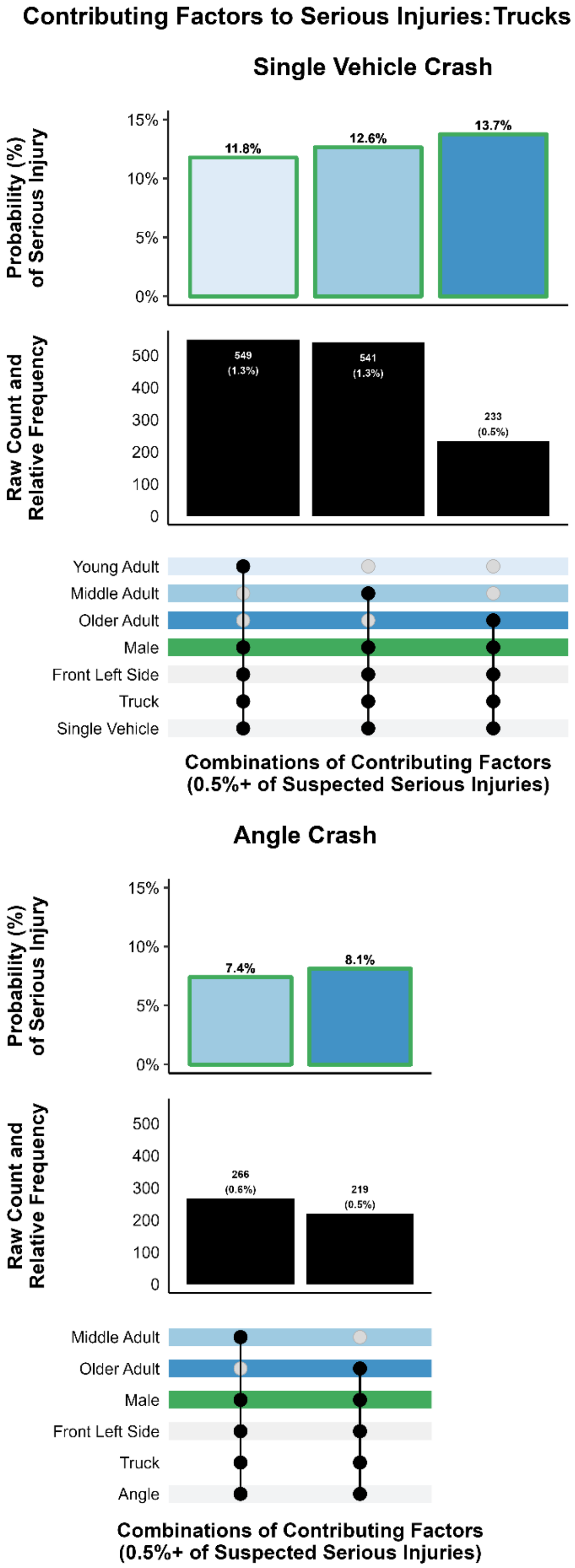

Fig A7. Upset plot of suspected serious injuries within Trucks, as associated with person and vehicle variables (black dots) and their intersections (black lines). Variable combinations are displayed if they represent at least 0.5% of all suspected serious injuries. Black bars show the raw suspected serious injury count of each variable combination, and its relative frequency (percentage) of all suspected serious injuries. Colored bars show the predicted probability of suspected serious injury for each variable combination, with the bar outline color indicating sex, and the bar fill indicating age group.

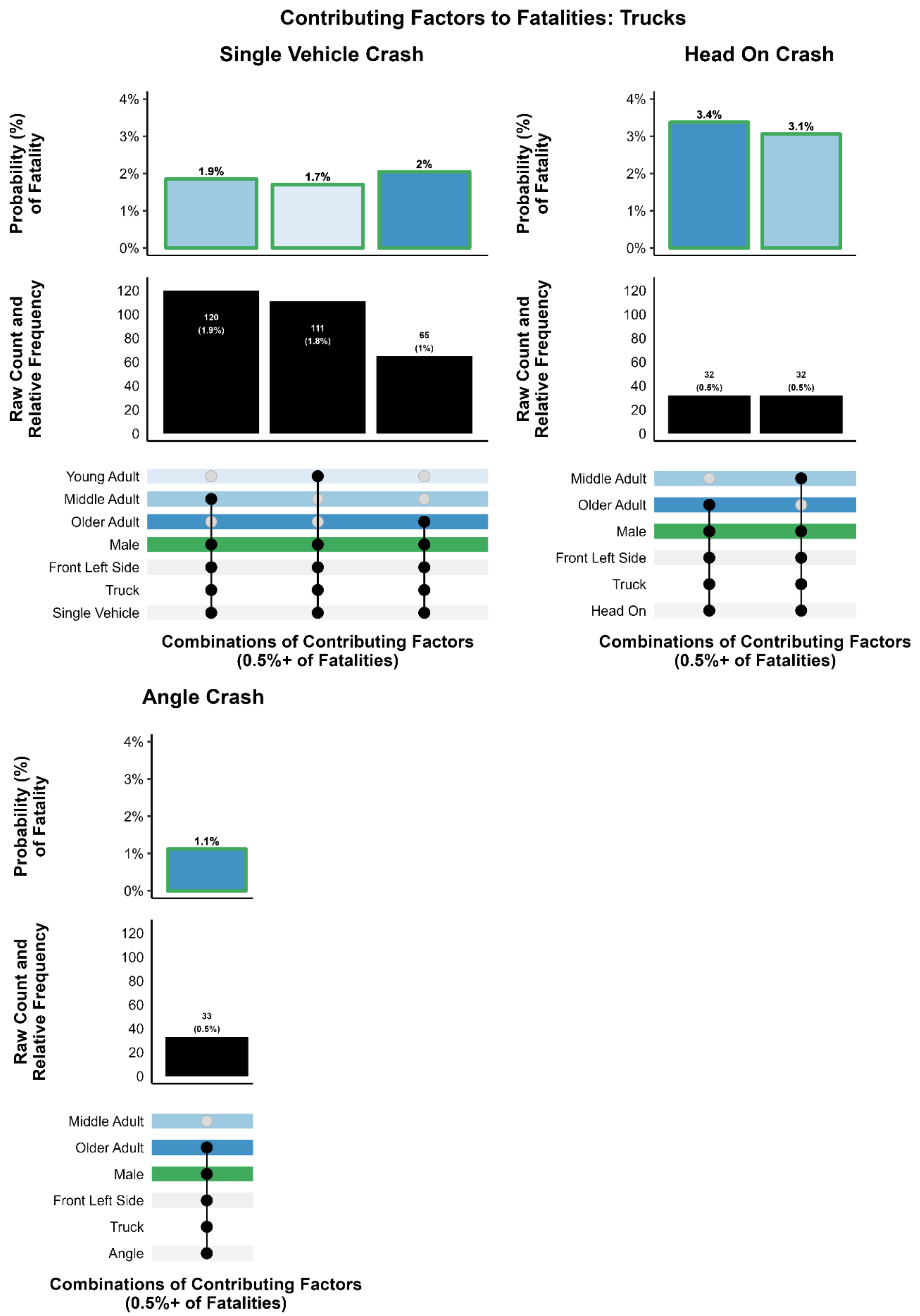

Fig A8. Upset plot of fatalities within Trucks, as associated with person and vehicle variables (black dots) and their intersections (black lines). Variable combinations are displayed if they represent at least 0.5% of all fatalities. Black bars show the raw fatality count of each variable combination, and its relative frequency (percentage) of all fatalities. Colored bars show the predicted probability of fatality for each variable combination, with the bar outline color indicating sex, and the bar fill indicating age group.

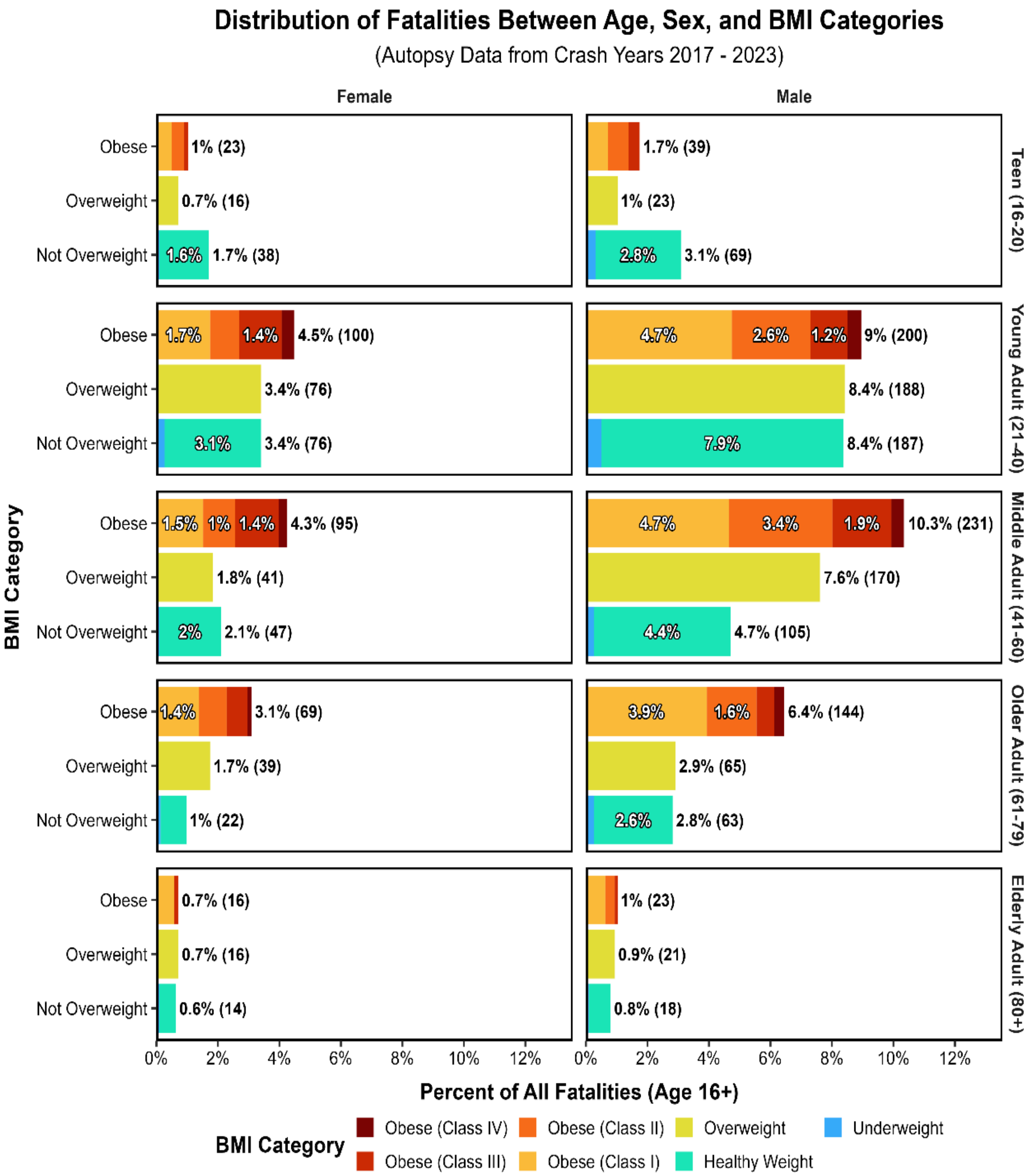

Fig. A9. Distribution of fatalities between BMI categories, subdivided by sex and age group.