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Applying the Crash Trifecta Approach to SHRP 2 Data

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LIST OF ABBREVIATIONS AND SYMBOLS

NDS	Naturalistic Driving Study
SCE	safety-critical event
SHRP 2	Second Strategic Highway Research Program
SV	subject vehicle
TI	transient inattention
TRB	Transportation Research Board
UB	unsafe behavior
UE	unexpected event
V2	other vehicle
VTTI	Virginia Tech Transportation Institute

CHAPTER 1. INTRODUCTION

Understanding the events leading up to motor vehicle crashes is crucial to preventing these crashes in the first place. Crash causation research identifies factors and mechanisms that increase crash risk and typically emphasizes a single critical reason as a primary proximal cause in a safety-critical event (SCE). This focus on a unitary critical reason does not allow for the specification of any factor other than the critical reason as directly contributing to the crash/event genesis. Realistically, however, SCEs often have more than one contributing factor. Non-critical reason factors may include ongoing pre-event behaviors, such as speeding, or transient, precipitating errors, such as those that occur due to distraction or inattention (Bocanegra et al., 2010). As described by Dunn et al. (2014), the crash trifecta model does not consider crash genesis as a simple unitary element, but rather as a convergence of elements. Specifically, the crash trifecta model is defined as three separate, converging elements:

1. Unsafe pre-incident behavior or maneuver (e.g., speeding, tailgating);
2. Transient driver inattention, either related (e.g., mirror use) or unrelated (e.g., reaching for an object) to driving; and
3. An unexpected traffic event (e.g., unexpected stopping by the vehicle ahead).

An example of the crash trifecta model is presented in Figure 1, which shows an at-fault truck crash (Dunn et al., 2014). The first crash trifecta element in this example is the unsafe pre-incident driving behavior, in this case tailgating. This is essentially a voluntary behavior and may be ongoing prior to the SCE. Other examples of unsafe pre-incident driving behavior include speeding; aggressive driving; improper turning; stop sign or signal violation; drowsy, inattentive, or distracted driving; excessive or sudden braking/stopping; and illegal passing. The second crash trifecta element is transient driver inattention. Although drivers often experience transient inattention, the rate and length of these periods can be diminished by reducing or eliminating associated behaviors, such as texting while driving (Knipling, 2009). The third element is an unexpected traffic event, which refers to a completely random event or an unexpected action taken by another actor in the event. These are events over which the driver has no control. In the example shown in Figure 1, the appearance of a deer on the road results in the lead vehicle braking suddenly (Dunn et al., 2014).

As Figure 1 illustrates, the combination of the individual elements creates a scenario that results in an at-fault crash for the subject vehicle (SV) driver (the truck driver in this case). It is important to note that the crash trifecta model can apply to other types of SCEs, and also that it is not necessary for all three elements to be present for an SCE to occur. However, it is also possible that the SCE may be avoided if any one of the crash trifecta elements is absent. For instance, if the SV driver's eyes were on the forward roadway, rather than looking at the phone, they may have noticed the deer on the road. And despite the tailgating behavior, had the SV driver noticed the deer, it may have been possible to stop in time or to engage in an evasive maneuver to prevent contact with the lead vehicle. Similarly, if the SV driver had not been tailgating the lead vehicle when the deer appeared on the road, there would have been more time for the driver to focus attention back on the forward roadway and engage in an evasive maneuver to avoid a collision. However, the combination of all three crash trifecta elements creates a scenario in which a crash is almost unavoidable (Dunn et al., 2014).

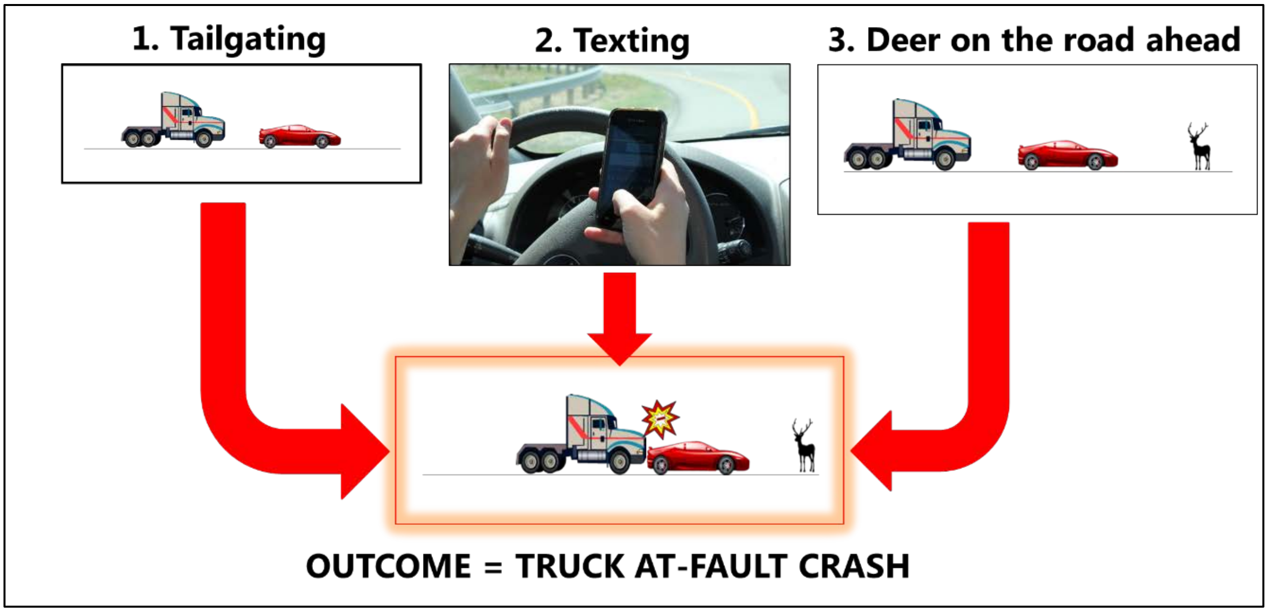

Figure 1. Diagram. The crash trifecta model applied to an at-fault truck crash.

Results from Phase I of the Crash Trifecta Study showed that the presence of all three crash trifecta elements increased as the severity of the SCE increased. Almost 25% of crashes and near-crashes included all three crash trifecta elements, while only 10% of crash-relevant conflicts included all three elements. Similarly, when focusing on at-fault SCEs, approximately 33% of crashes and over 25% of near-crashes were attributable to a combination of all three crash trifecta elements while the same was true for only 10% of crash-relevant conflicts. Unsafe driving behavior was, by far, the most prevalent crash trifecta element, with over 76% of crashes and 84% of near-crashes attributed to unsafe driving behavior, either as a single element or combined with additional elements. Given the limited number of crashes available in Phase I, it was not possible to identify trends in the presence of specific crash trifecta elements or to break the data down by incident type (e.g., rear-end, run-off road, side swipe, etc.) or crash severity (e.g., most severe, police-reportable, minor). More data, particularly crash data, were needed to develop the crash trifecta model further and gain a better understanding of the applicability of the model in crash causation research.

OVERVIEW OF THE CURRENT STUDY

The current study builds on the methods and results from Phase I (Dunn et al., 2014) by applying the crash trifecta model to the Second Strategic Highway Research Program (SHRP 2) Naturalistic Driving Study (NDS). Applying the model to SHRP 2 data greatly increases the number of SCEs available for analysis. Given the differing ages of the data sets used in Phase I compared to the more recent SHRP 2 study and the evolution of Virginia Tech Transportation Institute's (VTTI's) NDS reduction and coding process over time, there were variations in the way events were coded between the two data sets which made it difficult to directly compare the Phase 1 and Phase II results. For instance, curb strikes in Phase I were separated out, despite technically being defined as crashes due to the transfer of kinetic energy that occurs when a vehicle hits a curb. Additionally, a number of the data sets in Phase I did not provide information on curb strike severity, so there was no way to ascertain if the curb strike was minor (i.e., clipping the curb at low speed while parking) or more serious (i.e., hitting the median at high speed on a freeway); thus, all curb strikes were excluded from the Phase I analysis. Coding of curb strikes in the SHRP 2 data set was slightly different, as the crash severity variable could be used to separate out low-risk tire strikes from other curb strikes with an increased risk element (i.e., SCE would have been worse if curb had not been there). Therefore, low-risk tire strikes were excluded from the current Phase II analysis.

CHAPTER 2. METHODS

OVERVIEW OF THE DATA SET USED IN THE CURRENT STUDY

The current Phase II study was a secondary analysis of the SHRP 2 NDS data set. The SHRP 2 NDS ran from October 2010 through December 2013 and is the largest study of its kind ever conducted. The study collected continuous driving information on more than 3,000 light-vehicle drivers who covered approximately 32 million miles of driving at six different study sites throughout the United States. The drivers included men and women of various age groups, from different geographic areas, driving different types of light vehicles. See Dingus et al.'s Transportation Research Board (TRB) report, Naturalistic Driving Study: Technical Coordination and Quality Control (2015), for a complete description of the study's data collection methods and procedures, instrumentation, quality control, and project management.

DATA SET FORMATTING

Similar to Dunn et al. (2014), the crash trifecta model was applied to SCEs found in the SHRP 2 data set. Definitions were based on the SHRP 2 Researcher Dictionary for Video Reduction Data (Version 3.4) available on the Insight SHRP 2 NDS website (https://insight.shrp2nds.us).

- *Crash:* Any contact that the subject vehicle has with an object, either moving or fixed, at any speed in which kinetic energy is measurably transferred or dissipated. Also includes non-premeditated departures of the roadway where at least one tire leaves the paved or intended travel surface of the road. Includes contact with other vehicles, roadside barriers (including curbs), objects on or off of the roadway, pedestrians, cyclists, or animals. Roadway departures resulting from evasive maneuvers are considered non-premeditated and are also classified as crashes.

- *Near-Crash:* Any circumstance that requires a rapid evasive maneuver by the subject vehicle or any other vehicle, pedestrian, cyclist, or animal to avoid a crash. Near-crashes must meet the following four criteria: 1) Not a crash – The vehicle must not make contact with any object, moving or fixed, and the maneuver must not result in a road departure. 2) Not pre-meditated – The maneuver performed by the subject must not be pre-meditated. This criterion does not rule out near-crashes caused by unexpected events experienced during a pre-meditated maneuver (e.g., a premeditated aggressive lane change resulting in a conflict with an unseen vehicle in the adjacent lane that requires a rapid evasive maneuver by one of the vehicles). 3) Evasion required – An evasive maneuver to avoid a crash was required by either the subject or another vehicle, pedestrian, animal, etc. An evasive maneuver is defined as steering, braking, accelerating, or combination of control inputs that is performed to avoid a potential crash. 4) Rapidity required – The required evasive maneuver must also require rapidity. Rapidity refers to the swiftness of the response required given the amount of time from the beginning of the subject's reaction and the potential time of impact.

Crash-relevant conflicts were unavailable in the SHRP 2 NDS data set. Two additional variables were incorporated in the current study to allow for closer investigation of the elements contributing to crashes and near-crashes. Crash severity and incident type were included, based on the rationale that not all crash severities or types would comprise the same contributing factors. For example, it is highly likely that a severe run-off road crash would have different contributing factors than a minor rear-end collision. In other words, not all crashes and near-crashes are created equal and lumping them all together may blur any useful distinctions identified by the crash trifecta model.

There are four levels of crash severity, which are defined as follows:

- *Most Severe (Level I):* Any crash that includes an airbag deployment; any injury of driver, pedal cyclist, or pedestrian; a vehicle roll over; a high Delta V; or that requires vehicle towing. Injury if present should be sufficient to require a doctor's visit, including those self-reported and those apparent from video. A high Delta V is defined as a change in speed of the subject vehicle in any direction during impact greater than 20mph (excluding curb strikes) or acceleration on any axis greater than +/-2g (excluding curb strikes).

- *Police-Reportable Crash (Level II):* A police-reportable crash that does not meet the requirements for a Level I crash. Includes sufficient property damage that it is police reportable (minimum of ~$1500 worth of damage, as estimated from video). Also includes crashes that reach an acceleration on any axis greater than +/-1.3g (excluding curb strikes). Most large animal strikes and sign strikes are included here.

- *Minor Crash (Level III):* Most crashes not included above are Level III crashes. Includes physical contact with another object but with minimal damage. Includes most road departures (unless criteria for a more severe crash are met), small animal strikes, all curb and tires strikes potentially in conflict with oncoming traffic, and other curb strikes with an increased risk element (e.g., would have resulted in worse had curb not been there, usually related to some kind of driver behavior or state).

- *Low-Risk Tire Strike (Level IV):* Tire strike only with little/no risk element (e.g., clipping a curb during a tight turn). These were excluded from the current crash trifecta analysis.

The SHRP 2 NDS Researcher Dictionary for Safety Critical Event Video Reduction Data (https://insight.shrp2nds.us) lists 17 different categories for incident type. Table 1 provides the incident types included in the current study and a brief definition. Complete descriptions and illustrations of each incident type can be found in Appendix A.

Table 1. Definitions of incident types and categories.

Incident Type	Category Definition
Animal-Related	Subject vehicle (SV) makes contact or nearly makes contact with any type of living animal, which is on a trafficway or on a sidewalk.
Backing into Traffic	Vehicle backs into traffic flow
Backing (fixed object)	Vehicle backs into a non-moving, fixed object
Opposite Direction (head-on or sideswipe)	SV and other vehicle (V2) make or nearly make contact when the vehicles were traveling in opposite directions.
Other	Interaction with any non-motorist conveyance, non-motorist, or motorist not included in the other categories.
Pedal Cyclist-Related	Interaction with a person on any type of self-propelled pedaled cycle, including bicycles, tricycles, and unicycles.
Pedestrian-Related	SV makes contact or nearly makes contact with a pedestrian.
Rear-End (striking)	SV makes contact or nearly makes contact with any portion of the back of the vehicle in front (V2).
Rear-End (struck)	Vehicle behind (V2) makes contact or nearly makes contact with any portion of the back of the SV.
Road Departure (end)	Any tire on the SV leaves the end of the roadway.
Road Departure (left or right)	Any tire on the SV leaves the roadway, beyond the shoulder or onto median, on the left or right side of the roadway. Includes interaction with roadside barriers and curbs.
Sideswipe (same direction)	SV is struck or nearly struck by V2, or strikes or nearly strikes another vehicle (V2) on either the driver or passenger side of the vehicle when the vehicles were traveling in the same direction.
Straight Crossing Path	Vehicle (SV or V2) crosses another vehicle path perpendicularly. Both vehicles intending to proceed straight across each other's paths.
Turn Across Path	Vehicle (SV or V2) crosses in front of the path of another vehicle. Vehicles were initially on the same roadway, either in the same or opposite directions.
Turn into Path (opposite direction)	Vehicle (SV or V2) turns into the path of another vehicle. Vehicles were initially on different trafficways, traveling perpendicular to each other.
Turn into Path (same direction)	Vehicle (SV or V2) turns into the path of another vehicle. Vehicles were initially on different trafficways traveling perpendicular to each other.

DATA REDUCTION

The Phase II data reduction process was the same as that in Phase I (Dunn et al., 2014). The SV driver behavior variable was used to determine if an unsafe driving behavior was present during the SCE. Examples of unsafe driving behavior included speeding; aggressive driving; improper turning; stop sign or signal violation; drowsy, inattentive, or distracted driving; excessive or sudden braking/stopping; following too close; and illegal passing. See Appendix B for a complete list of unsafe driving behaviors in the SHRP 2 NDS data set. In regard to transient driver inattention, assessment of inattention was based on previously reduced and coded eye-glance data, where the total time the SV driver's eyes were off the forward roadway during the 5 seconds prior to an SCE was calculated. As in Phase I, the current study used a threshold of more than 1 second for the determination of transient driver inattention. Thus, if the SV driver's eyes were off the forward roadway for a total of more than 1 second prior to the triggering event, transient driver inattention was deemed to be present.

Additional data reduction was completed in order to determine if an unexpected traffic event occurred prior to, or during, the SCE. Data analysts examined the 10 seconds of video data prior to an SCE to determine if the SV driver experienced an unexpected event. Examples of an unexpected event include an animal, object, or debris on the road; another vehicle pulling out in front of the subject vehicle; a lead vehicle braking suddenly; another vehicle cutting in front of the subject vehicle; and changes in traffic occurring while the SV driver was not paying attention (e.g., traffic moving freely, SV driver looks away, and traffic stops).

A new requirement to the unexpected event coding from Phase I was added in order to ensure that the event was truly random and unexpected. The additional condition was that the other vehicle (V2) involved in the SCE (i.e., not the subject vehicle) had to do something truly unexpected. In other words, if V2 was driving normally and the SCE was due to an SV error or assumption, this was not coded as an unexpected event. For example, if the SV driver failed to check a blind spot and crashed into V2 when changing lanes, this would not be coded as an unexpected event. The SCE would only be coded as such if V2 did something that was truly unexpected, such as attempt to change lanes at the same time as the SV. Similarly, if the SV driver assumed V2 was going to proceed through an amber light, but instead V2 stopped and the was rear ended by the SV, this would not be coded as an unexpected event either. While it may seem that both of these examples would likely elicit a surprised response from the SV driver, leading data analysts to consider the SCE unexpected, the SCE would only be unexpected because of the mistaken assumptions or errors on the part of the SV driver, which would not be a truly random or unexpected event as the definition states. See Appendix C for the operational definition of an unexpected traffic event and the data reduction protocol.

Quality Control and Reliability

As in Phase I, the data reduction process for the unexpected event variable involved subjective interpretation of video data; thus, reliability estimates of data analysts' subjective judgments were crucial to the data reduction process. Approximately 95% of the SCEs that made up the initial data set of 4,246 events were reviewed by a second data analyst to determine inter-rater reliability. Of the 4,031 SCEs that underwent reliability checks, whole agreement between the analysts was achieved for 3,743 SCEs (92.8% agreement). In the 288 instances where the analysts did not initially agree in their judgment, they discussed their reasoning and reviewed the video together before arriving at a mutually agreeable final decision. The remaining 27 cases where the analysts could not mutually agree on a final decision were passed on to the project manager, who made a final decision.

CHAPTER 3. RESULTS

Only those SCEs with data available for all three of the crash trifecta elements were included in the analysis. Events with any proportion of unusable eye glance data, or less than 4.9 seconds of usable eye glance data, were excluded from the analysis. The remaining events were then classified in terms of the joint presence or absence of the three trifecta elements. Table 2 shows the severity levels of the 4,101 SCEs included in the crash trifecta analysis.

Table 2. Crash trifecta event classification by severity.

Event Severity	Number of Crash Trifecta Events (n = 4,101)	Percent of Total Events
Crashes	1,466	100.00%
Most Severe	*109*	*7.44%*
Police-Reportable	*154*	*10.50%*
Minor	*605*	*41.27%*
Low-Risk Tire Strike	*598*	*40.79%*
Near-Crashes	2,635	100.00%

As mentioned earlier, despite technically falling under the definition of a crash, low-risk tire strikes were excluded from the analysis of crashes. Because they involve little to no risk element and lack potential for conflict with oncoming traffic, it is highly likely that low-risk tire strikes are inherently different from other crashes. Unfortunately, 40% of the crashes in the SHRP 2 NDS data set were low-risk tire strikes, meaning the number of crashes available for more in-depth analysis was greatly reduced.

Table 3 shows the presence of each crash trifecta element (and combination of elements) by SCE severity. Approximately 46% of the SCEs were attributed to a single crash trifecta element. Specifically, 45% of crashes, 46% of near-crashes, and 52% of low-risk tire strikes had only one crash trifecta element present. Unsafe driving behavior was the most common element present in crashes and low-risk tire strikes. When paired with transient inattention, these two elements contributed (either individually or combined) to just over 60% of crashes and 80% of low-risk tire strikes. The most common element present in near-crashes, however, was an unexpected traffic event, which was present in almost 75% of near-crashes. Combined with unsafe driving behavior, these two elements contributed to almost 67% of near-crashes. A surprisingly small percentage of crashes (7%) included all three of the crash trifecta elements. All three elements were present at double that rate (14%) for near-crashes.

Table 3. Crash trifecta elements by event classification.

Crash Trifecta Elements	Crash (*n* = 868)	Near-Crash (*n* = 2,635)	Low-Risk Tire Strikes (*n* = 598)	Total (*n* = 4,101)
None	11.9%	6.9%	17.4%	9.5%
Unexpected Event (UE)	8.4%	32.8%	0.5%	22.9%
Transient Inattention (TI)	7.1%	1.6%	6.4%	3.5%
Unsafe Behavior (UB)	29.2%	11.7%	44.7%	20.2%
UE + TI	2.5%	7.0%	0.5%	5.1%
UE + UB	8.0%	20.1%	0.8%	14.7%
UB + TI	26.0%	5.5%	29.4%	13.3%
Crash Trifecta	6.9%	14.4%	0.3%	10.8%
Total	**100.0%**	**100.0%**	**100.0%**	**100.0%**

Table 4 shows the presence of the crash trifecta elements by SCE severity for SCEs where the SV driver was deemed to be at fault. In regard to individual crash trifecta elements, unsafe driving behavior was coded in over 25% of the at-fault SCEs compared to 3% for transient driver inattention and 12% for unexpected traffic events. Unsafe driving behavior contributed to 80% of at-fault crashes and 67% of at-fault near-crashes. Combined with transient inattention, these two elements contributed to almost 70% of at-fault crashes and 80% of low-risk tire strikes. Just over 55% of at-fault near-crashes were attributed to unsafe driving behavior and an unexpected traffic event, either alone or combined. The majority of at-fault near-crashes had at least two crash trifecta elements present, with almost 20% having all three crash trifecta elements present. Surprisingly, only 7% of at-fault crashes included all three crash trifecta elements.

Table 4. At-fault crash trifecta elements by event classification.

Crash Trifecta Elements	Crash (*n* = 715)	Near-Crash (*n* = 1,679)	Low-Risk Tire Strikes (*n* = 589)	Total (*n* = 2,983)
None	8.3%	8.3%	17.7%	10.1%
Unexpected Event (UE)	7.1%	18.1%	0.2%	11.9%
Transient Inattention (TI)	3.2%	2.0%	6.4%	3.2%
Unsafe Behavior (UB)	34.8%	17.6%	45.1%	27.2%
UE + TI	2.0%	5.2%	0.3%	3.5%

Crash Trifecta Elements	Crash (*n* = 715)	Near-Crash (*n* = 1,679)	Low-Risk Tire Strikes (*n* = 589)	Total (*n* = 2,983)
UE + UB	6.7%	21.2%	0.2%	13.6%
UB + TI	30.9%	8.3%	29.9%	18.0%
Crash Trifecta	7.0%	19.3%	0.2%	12.5%
Total	**100.0%**	**100.0%**	**100.0%**	**100.0%**

Given the likelihood of differences between particular crash types (e.g., rear-end versus road departure), the dataset was broken down by incident type. Low-risk tire strikes were excluded from the remaining analyses. Table 5 shows the presence of the crash trifecta elements by incident type for crashes. The most common types of crashes were road departures (left or right), rear end (striking), rear end (struck), and animal related. See Figure 2 in Appendix A for an illustrated representation of each incident type. For the purpose of these analyses, the "other" incident type category was excluded, as this was a catch-all for incidents that did not fit into the other specific categories, causing a probable high variability in causal factors.

Not surprisingly, unsafe driving behavior, either alone or combined with additional crash trifecta elements, was a major contributor to almost all the different incident types. Most notably, over half of the 360 road departure (left or right) crashes were due to unsafe driving behavior and 40% were due to a combination of unsafe driving behavior and transient inattention. Rear end (striking) crashes were also largely attributed to unsafe driving behavior with over 75% of rear end crashes including this element. Approximately 60% of rear end (striking) crashes had at least two crash trifecta elements present, with just over 25% having all three elements present. An unexpected event, either alone or combined with additional elements, contributed to *all* animal related crashes, which was to be expected, as these incident types are nearly always associated with the unpredictability of an animal appearing on the road. Interestingly, just over 25% of animal related crashes were attributed to an unexpected event combined with unsafe driving behavior, which suggests that these crashes may have been avoided if the driver had not been engaging in unsafe driving behavior (e.g., speeding or distracted). The contribution of transient inattention to backing into traffic, backing (fixed object), and rear end (struck) incident types was somewhat misleading, as the actions required of the SV driver during these crashes either necessitated their eyes being off the forward roadway (in the case of backing up and using just the rearview mirror) or did not necessitate their eyes being on the forward roadway (in the case of being stopped and struck from the rear). Despite this, both of these situations would lead to a coding judgment of transient inattention based on duration of time the SV drivers' eyes were off the forward roadway.

Table 5. Crash trifecta elements by incident type for crashes (low-risk tire strikes excluded).

Incident Type	None	Unexpected Event (UE)	Transient Inattention (TI)	Unsafe Behavior (UB)	UE + TI	UE + UB	UB + TI	Crash Trifecta	*Incident Type Count*
Animal Related	0%	46.2%	0%	0%	13.5%	26.9%	0%	13.5%	*52*
Backing into Traffic	14.3%	14.3%	14.3%	7.1%	7.1%	14.3%	28.6%	0%	*14*
Backing (fixed object)	0%	0%	13.3%	13.3%	0%	0%	73.3%	0%	*15*
Opposite Direction (head-on or sideswipe)	0%	20.0%	20.0%	20.0%	0%	20.0%	0%	20.0%	*5*
Other	15.3%	27.8%	9.7%	19.4%	5.6%	4.2%	13.9%	4.2%	*72*
Pedalcyclist Related	0%	0%	0%	0%	100.0%	0%	0%	0%	*1*
Pedestrian Related	50.0%	0%	0%	0%	0%	0%	0%	50.0%	*2*
Rear End (striking)	9.9%	6.8%	3.1%	14.5%	3.8%	18.3%	16.8%	26.7%	*131*
Rear End (struck)	47.0%	0%	42.2%	6.0%	0%	0%	3.6%	1.2%	*83*
Road Departure (end)	36.4%	0%	9.1%	33.3%	0%	0%	21.2%	0%	*33*
Road Departure (left or right)	5.6%	0%	1.1%	51.7%	0%	0.6%	41.1%	0%	*360*
Sideswipe (same direction)	10.0%	3.3%	3.3%	10.0%	6.7%	30.0%	30.0%	6.7%	*30*
Straight Crossing Path	6.7%	26.7%	6.7%	26.7%	6.7%	13.3%	0%	13.3%	*15*
Turn Across Path	0%	17.4%	4.4%	17.4%	0%	34.8%	13.0%	13.0%	*23*
Turn into Path (opposite direction)	5.3%	21.1%	5.3%	10.5%	5.3%	5.3%	36.8%	10.5%	*19*
Turn into Path (same direction)	0%	33.3%	0%	8.3%	0%	16.7%	16.7%	25.0%	*12*

Table 6. Crash trifecta elements by incident type for at-fault crashes (low-risk tire strikes excluded).

Incident Type	None	Unexpected Event (UE)	Transient Inattention (TI)	Unsafe Behavior (UB)	UE + TI	UE + UB	UB + TI	Crash Trifecta	*Incident Type Count*
Animal Related	0%	46.2%	0%	0%	13.5%	26.9%	0%	13.5%	*52*
Backing into Traffic	0%	0%	0%	16.7%	0%	16.7%	66.7%	0%	*6*
Backing (fixed object)	0%	0%	13.3%	13.3%	0%	0%	73.3%	0%	*15*
Opposite Direction (head-on or sideswipe)	0%	0%	0%	50.0%	0%	50.0%	0%	0%	*2*
Other	14.3%	28.6%	10.0%	20.0%	4.3%	4.3%	14.3%	4.3%	*70*
Pedalcyclist Related	.	.	.	.	.	.	.	.	*0*
Pedestrian Related	0%	0%	0%	0%	0%	0%	0%	100.0%	*1*
Rear End (striking)	10.6%	4.1%	3.3%	15.5%	3.3%	17.9%	17.9%	27.6%	*123*
Rear End (struck)	42.9%	0%	14.3%	42.9%	0%	0%	0%	0%	*7*
Road Departure (end)	36.4%	0%	9.1%	33.3%	0%	0%	21.2%	0%	*33*
Road Departure (left or right)	5.6%	0%	1.1%	51.7%	0%	0%	41.1%	0%	*360*
Sideswipe (same direction)	6.7%	6.7%	0%	20.0%	0%	13.3%	46.7%	6.7%	*15*
Straight Crossing Path	0%	0%	16.7%	66.7%	0%	0%	0%	16.7%	*6*
Turn Across Path	0%	10.0%	10.0%	20.0%	0%	20.0%	30.0%	10.0%	*10*
Turn into Path (opposite direction)	0%	0%	0%	18.2%	0%	0%	63.6%	18.2%	*11*
Turn into Path (same direction)	0%	0%	0%	25.0%	0%	25.0%	50.0%	0%	*4*

Table 7. Crash trifecta elements by incident type for severe crashes.

Incident Type	None	Unexpected Event (UE)	Transient Inattention (TI)	Unsafe Behavior (UB)	UE + TI	UE + UB	UB + TI	Crash Trifecta	*Incident Type Count*
Animal Related	0%	45.5%	0%	0%	9.1%	36.4%	0%	9.1%	*11*
Backing into Traffic	14.3%	28.6%	0%	14.3%	0%	28.6%	28.6%	0%	*7*
Backing (fixed object)	0%	0%	13.3%	13.3%	0%	0%	73.3%	0%	*15*
Opposite Direction (head-on or sideswipe)	0%	0%	0%	0%	0%	0%	0%	100.0%	*1*
Other	0%	0%	33.3%	33.3%	0%	0%	33.3%	0%	*3*
Pedalcyclist Related	0%	0%	0%	0%	0%	0%	0%	0%	*0*
Pedestrian Related	100.0%	0%	0%	0%	0%	0%	0%	0%	*1*
Rear End (striking)	6.3%	7.6%	2.5%	16.5%	2.5%	17.7%	16.5%	30.4%	*79*
Rear End (struck)	51.1%	0%	34.0%	8.5%	0%	0%	4.3%	2.1%	*47*
Road Departure (end)	83.3%	0%	0%	0%	0%	0%	16.7%	0%	*6*
Road Departure (left or right)	3.0%	0%	0%	72.7%	0%	3.0%	21.2%	0%	*33*
Sideswipe (same direction)	0%	0%	0%	13.3%	6.7%	33.3%	33.3%	13.3%	*15*
Straight Crossing Path	7.1%	21.4%	7.1%	28.6%	7.1%	14.3%	0%	14.3%	*14*
Turn Across Path	0%	19.1%	4.8%	19.1%	0%	33.5%	14.3%	9.5%	*21*
Turn into Path (opposite direction)	5.9%	17.7%	5.9%	11.8%	5.9%	0%	41.2%	11.8%	*17*
Turn into Path (same direction)	0%	28.6%	0%	0%	0%	28.6%	28.6%	14.3%	*7*

Table 8. Crash trifecta elements by incident type for at-fault, severe crashes.

Incident Type	None	Unexpected Event (UE)	Transient Inattention (TI)	Unsafe Behavior (UB)	UE + TI	UE + UB	UB + TI	Crash Trifecta	*Incident Type Count*
Animal Related	0%	45.5%	0%	0%	9.1%	36.4%	0%	9.1%	*11*
Backing into Traffic	0%	0%	0%	25.0%	0%	25.0%	50.0%	0%	*4*
Backing (fixed object)	.	.	.	.	.	.	.	.	*0*
Opposite Direction (head-on or sideswipe)	.	.	.	.	.	.	.	.	*0*
Other	0%	0%	33.3%	33.3%	0%	0%	33.3%	0%	*3*
Pedalcyclist Related	.	.	.	.	.	.	.	.	*0*
Pedestrian Related	.	.	.	.	.	.	.	.	*0*
Rear End (striking)	6.8%	4.1%	2.7%	17.8%	1.4%	17.8%	17.8%	31.5%	*73*
Rear End (struck)	33.3%	0%	16.7%	50.0%	0%	0%	0%	0%	*6*
Road Departure (end)	83.3%	0%	0%	0%	0%	0%	16.7%	0%	*6*
Road Departure (left or right)	3.0%	0%	0%	72.7%	0%	3.0%	21.2%	0%	*33*
Sideswipe (same direction)	0%	0%	0%	22.2%	0%	22.2%	44.4%	11.1%	*9*
Straight Crossing Path	0%	0%	16.7%	66.7%	0%	0%	0%	16.7%	*6*
Turn Across Path	0%	10.0%	10.0%	20.0%	0%	10.0%	30.0%	10.0%	*10*
Turn into Path (opposite direction)	0%	0%	0%	18.2%	0%	0%	63.6%	18.2%	*11*
Turn into Path (same direction)	0%	0%	0%	0%	0%	33.3%	66.7%	0%	*3*

Table 6 shows the presence of the crash trifecta elements by incident type for at-fault crashes. Similar to the previous results, unsafe driving behavior, either alone or combined with additional crash trifecta elements, contributed to a large proportion of at-fault crashes, regardless of the incident type. Unsafe driving behavior alone or combined with transient inattention contributed to approximately 33% of rear end (striking); 55% of road departure (end); 93% of road departure (left or right); 67% of sideswipe (same direction); and 82% of turn into path (opposite direction) at-fault crashes. These results highlight the vast number of crashes that would essentially be preventable if drivers engaged in safe driving behavior and paid attention to the forward roadway while driving.

When looking specifically at severe crashes, which incorporated "most severe" and "police-reportable" crashes, the number of cases dropped significantly, but still provided insight into the contributing crash trifecta elements. Table 7 and Table 8 show the presence of the crash trifecta elements by incident type for severe crashes and severe at-fault crashes. Most notably, approximately 33% of rear end (striking) severe crashes and severe at-fault crashes were attributed to the crash trifecta. Unsafe driving behavior still played a dominant causal role in the majority of the incident types, including sideswipe (same direction), straight crossing path, turn across path, turn into path (opposite direction), and turn into path (same direction). This was especially true when unsafe driving behavior was combined with transient inattention. These two elements combined contributed to a large proportion of severe crashes, particularly those in which the SV driver was deemed to be at-fault.

Table 9 shows the presence of the crash trifecta elements by incident type for near-crashes. The larger number of near-crashes, compared to crashes, provided the opportunity to examine incident types that did not have a high enough incident type count in the crash analysis (e.g., pedestrian and pedalcyclist related incidents). Unlike crashes, the majority of different types of near-crashes were predominantly attributed to an unexpected event, either alone or combined with unsafe driving behavior. Over 60% of pedestrian related, sideswipe (same direction), turn into path (opposite direction), and turn into path (same direction) near-crashes were attributed to an unexpected traffic event alone or combined with unsafe driving behavior. This rose to over 70% for animal-related, pedalcyclist-related, and turn across path near-crashes. Clearly, unpredictability plays a large role in the occurrence of near-crashes. Relative to crashes, the presence of transient inattention was low in most types of near-crash incidents, which makes sense, given that a driver is more likely to be able to engage in a successful avoidance maneuver if they are paying attention to the forward roadway and have sufficient time to respond to the imminent threat. The exception was road departure (left or right), for which almost 25% of near-crashes were attributed to unsafe driving behavior and transient inattention, and pedestrian related and rear end (striking), for both of which approximately 20% of near-crashes were attributed to the crash trifecta.

Focusing on at-fault near-crashes provided a slightly different picture than above (see Table 10), which is to be expected given that the definition of "at-fault" requires the SV driver to have committed an error that led to the SCE. As expected, since unsafe driving behavior is more likely to lead to errors, the presence of unsafe driving behavior was higher in at-fault near-crashes than in all near-crashes (i.e., regardless of fault). Over half of pedalcyclist-related, pedestrian-related, rear end (striking), straight crossing path, and turn into path (opposite direction) near-crashes were attributed to an unexpected event and unsafe driving behavior, either alone or combined.

This proportion rose to roughly 67% for sideswipe (same direction) and turn across path near-crashes. Around 20% of pedalcyclist related, pedestrian related, rear end (striking) and turn across path near-crashes were attributed to the crash trifecta. The crash trifecta appears to have greater explanatory value for at-fault near-crashes than at-fault crashes; however, the number of at-fault crashes was relatively low compared to at-fault near-crashes, meaning some incident type categories could not be analyzed.

Table 11 shows the number of crash trifecta elements by incident type for crashes and near-crashes. This information illustrates the explanatory value of the crash trifecta for the different incident types. For example, rear end (struck) and road departure (end) crashes are not well explained by the crash trifecta, as 47% and 36% of these types of crashes, respectively, had zero crash trifecta elements present. The crash trifecta was more applicable to rear end (striking) and sideswipe (same direction) crashes, on the other hand, with a respective 66% and 73% having two or more crash trifecta elements present. The Fisher's test results (see Table 12) indicate a significant difference in the proportion of events with zero, one, two, or three crash trifecta elements present for rear end (striking), rear end (struck), road departure (left or right), and sideswipe (same direction) crashes and near-crashes. The crash trifecta was more applicable to rear end (striking), road departure (left or right) and sideswipe (same direction) crashes compared to near-crashes. In rear end (striking) incidents, all three crash trifecta elements were present in 26.7% of crashes versus 19.6% of near-crashes. In road departure (left or right) incidents, both crashes and near-crashes most frequently had a single crash trifecta element present (52.8% and 71.4% respectively); however, two crash trifecta elements were present in 41.7% of crashes and 24.3% of near-crashes. Sideswipe (same direction) incidents had a single crash trifecta element present in 16.7% of crashes and 57.8% of near-crashes. Two elements were present in twice as many sideswipe (same direction) crashes (66.7%) as near-crashes (31.5%).

Table 9. Crash trifecta elements by incident type for near-crashes.

Incident Type	None	Unexpected Event (UE)	Transient Inattention (TI)	Unsafe Behavior (UB)	UE + TI	UE + UB	UB + TI	Crash Trifecta	*Incident Type Count*
Animal Related	0%	56.8%	0%	0.8%	12.8%	20.8%	0%	8.8%	*125*
Backing into Traffic	3.5%	37.9%	0%	0%	13.8%	13.8%	10.3%	20.7%	*29*
Backing (fixed object)	.	.	.	.	.	.	.	.	*0*
Opposite Direction (head-on or sideswipe)	0%	44.1%	2.9%	11.8%	8.8%	17.7%	11.8%	2.9%	*34*
Other	10.4%	16.7%	2.1%	41.7%	4.2%	6.3%	12.5%	6.3%	*48*
Pedalcyclist Related	0%	40.0%	0%	6.7%	6.7%	30.0%	3.3%	13.3%	*30*
Pedestrian Related	4.2%	35.2%	0%	2.8%	8.5%	25.4%	2.8%	21.1%	*71*
Rear End (striking)	10.5%	23.7%	2.1%	11.1%	6.4%	22.3%	4.3%	19.6%	*1,311*
Rear End (struck)	15.8%	0%	0%	26.3%	0%	0%	36.8%	21.1%	*19*
Road Departure (end)	0%	0%	0%	66.7%	0%	0%	33.3%	0%	*3*
Road Departure (left or right)	2.9%	2.9%	4.3%	64.3%	0%	0%	24.3%	1.4%	*70*
Sideswipe (same direction)	2.7%	47.6%	0.5%	9.7%	7.5%	20.2%	3.8%	8.1%	*372*
Straight Crossing Path	0%	36.7%	2.5%	13.9%	17.7%	12.7%	10.1%	6.3%	*79*
Turn Across Path	2.7%	45.3%	0.7%	7.4%	6.1%	25.0%	3.4%	9.5%	*148*
Turn into Path (opposite direction)	3.3%	43.0%	1.7%	9.1%	3.3%	20.7%	7.4%	11.6%	*121*
Turn into Path (same direction)	7.4%	48.0%	1.7%	6.9%	6.9%	13.7%	6.9%	8.6%	*175*

Table 10. Crash trifecta elements by incident type for at-fault near-crashes.

Incident Type	None	Unexpected Event (UE)	Transient Inattention (TI)	Unsafe Behavior (UB)	UE + TI	UE + UB	UB + TI	Crash Trifecta	*Incident Type Count*
Animal Related	0%	56.8%	0%	0.8%	12.8%	20.8%	0%	8.8%	*125*
Backing into Traffic	0%	16.7%	0%	0%	0%	33.3%	33.3%	16.7%	*6*
Backing (fixed object)	.	.	.	.	.	.	.	.	*0*
Opposite Direction (head-on or sideswipe)	0%	0%	8.3%	33.3%	8.3%	16.7%	33.3%	0%	*12*
Other	9.5%	7.1%	2.4%	47.6%	4.8%	7.1%	14.3%	7.1%	*42*
Pedalcyclist Related	0%	23.5%	0%	11.8%	11.8%	23.5%	5.9%	23.5%	*17*
Pedestrian Related	7.1%	23.8%	0%	4.8%	7.1%	28.6%	4.8%	23.8%	*42*
Rear End (striking)	11.3%	17.8%	2.1%	13.0%	5.5%	22.6%	4.9%	22.8%	*1,084*
Rear End (struck)	6.3%	0%	0%	31.3%	0%	0%	43.8%	18.8%	*16*
Road Departure (end)	0%	0%	0%	66.7%	0%	0%	33.3%	0%	*3*
Road Departure (left or right)	2.9%	1.5%	4.4%	65.2%	0%	0%	24.6%	1.5%	*69*
Sideswipe (same direction)	3.8%	10.0%	0%	37.5%	0%	17.5%	16.3%	15.0%	*80*
Straight Crossing Path	0%	11.4%	5.7%	31.4%	2.9%	14.3%	22.9%	11.4%	*35*
Turn Across Path	0%	8.9%	0%	22.2%	2.2%	35.6%	11.1%	20.0%	*45*
Turn into Path (opposite direction)	1.8%	3.6%	3.6%	20.0%	1.8%	34.6%	16.4%	18.2%	*55*
Turn into Path (same direction)	6.3%	4.2%	4.2%	25.0%	2.1%	16.7%	25.0%	16.7%	*48*

Table 11. Number of crash trifecta elements by incident type for crashes (low-risk tire strikes excluded) and near-crashes.

Incident Type	Crashes					Near-Crashes				
	Count	0	1	2	3	*Count*	0	1	2	3
Animal Related	*52*	0%	46.1%	40.4%	13.5%	*125*	0%	57.6%	33.6%	8.8%
Backing into Traffic	*14*	14.3%	35.7%	50.0%	0%	*29*	3.5%	37.9%	37.9%	20.7%
Backing (fixed object)	*15*	0%	26.7%	73.3%	0%	*0*	0%	0%	0%	0%
Opposite Direction (head-on or swipe)	*5*	0%	60.0%	20.0%	20.0%	*34*	0%	58.8%	38.2%	2.9%
Other	*72*	15.3%	56.9%	23.6%	4.2%	*48*	10.4%	60.4%	22.9%	6.3%
Pedalcyclist Related	*1*	0%	0%	100%	0%	*30*	0%	46.7%	40.0%	13.3%
Pedestrian Related	*2*	50.0%	0%	0%	50.0%	*71*	4.2%	38.0%	36.6%	21.1%
Rear End (striking)	*131*	9.9%	24.5%	38.9%	26.7%	*1,311*	10.5%	37.0%	32.9%	19.6%
Rear End (struck)	*83*	47.0%	48.2%	3.6%	1.2%	*19*	15.8%	26.3%	36.8%	21.1%
Road Departure (end)	*33*	36.4%	42.4%	21.2%	0%	*3*	0%	66.7%	33.3%	0%
Road Departure (left or right)	*360*	5.5%	52.8%	41.7%	0%	*70*	2.9%	71.4%	24.3%	1.4%
Sideswipe (same direction)	*30*	10.0%	16.7%	66.7%	6.7%	*372*	2.7%	57.8%	31.5%	8.1%
Straight Crossing Path	*15*	6.7%	60.0%	20.0%	13.3%	*79*	0%	53.2%	40.5%	6.3%
Turn Across Path	*23*	0%	39.1%	43.5%	17.4%	*148*	2.7%	53.4%	34.5%	9.5%
Turn into Path (opposite direction)	*19*	5.3%	36.8%	47.4%	10.5%	*121*	3.3%	53.7%	31.4%	11.6%
Turn into Path (same direction)	*12*	0%	41.7%	33.3%	25.0%	*175*	7.4%	56.6%	27.4%	8.6%

Table 12. Fisher's test results, comparing crashes (excluding low-risk tire strikes) to near-crashes for significant differences in proportion of events with zero, one, two, or three crash trifecta elements.

Incident Type	Fisher's Table Probability	P-Value
Animal Related	0.0099	0.3330
Backing into Traffic	0.0053	0.1649
Backing (fixed object)	-	-
Opposite Direction (head-on or sideswipe)	0.0861	0.3448
Other	0.0086	0.8472
Pedalcyclist Related	-	-
Pedestrian Related	-	-
Rear End (striking)	<0.0001	0.0193*
Rear End (struck)	<0.0001	<0.0001*
Road Departure (end)	-	-
Road Departure (left or right)	<0.0001	0.0031*
Sideswipe (same direction)	<0.0001	<0.0001*
Straight Crossing Path	0.0045	0.0712
Turn Across Path	0.0084	0.4011
Turn into Path (opposite direction)	0.0088	0.4136
Turn into Path (same direction)	0.0076	0.1935

*statistically significant
Note: Incident types without test results had insufficient counts for appropriate testing or drawing conclusions.

CHAPTER 4. CONCLUSIONS

The results of this study clearly show that elements well within a driver's control are at the core of the majority of SCEs. Unsafe driving behavior was the most prevalent crash trifecta element, occurring in 70% of crashes and 52% of near-crashes. Not surprisingly, the prevalence of unsafe driving behavior increased when focusing specifically on SCEs where the SV driver was deemed to be at-fault, with 80% of at-fault crashes and 66% of at-fault near-crashes attributed to unsafe driving behavior, either alone or combined with additional crash trifecta elements. This is consistent with most crash causation studies (e.g., National Highway Traffic Safety Administration, 2008; Dingus et al., 2006; Knipling, 2009). Indeed, a recent survey by the AAA Foundation for Traffic Safety (2016) found approximately 87% of drivers admitted to engaging in at least one risky behavior while driving within the past month. Unsafe behaviors included distracted driving, impaired driving, drowsy driving, speeding, running red lights, and not wearing a seatbelt. The pervasiveness of unsafe driving behavior highlights the complacency and culture of indifference among the general driving population. Results of the aforementioned survey indicated that, despite respondents perceiving unsafe driving behaviors, such as speeding or impaired driving, as serious threats to their personal safety, they also often admitted to engaging in those behaviors themselves (AAA, 2016). Unsafe driving behavior combined with transient inattention contributed to over 25% of crashes and almost 33% of at-fault crashes in the current study, compared to 5% of near-crashes and 8% of at-fault near-crashes, indicating that a crash is much more likely to occur if the unsafe driver is also not paying attention. Given the indifference to unsafe driving behavior, future advances in road safety may be reliant on developing effective distraction and inattention countermeasure technologies. Potential countermeasure technologies work in one of two ways: preventing inattention from occurring in the first place or mitigating the severity of the consequences after it has occurred (Victor, 2011). This is an active area of research with a variety of technologies currently available. However, many of these technologies have not been independently validated, and thus their effectiveness, reliability, and usefulness remain to be seen.

The prevalence of the remaining two crash trifecta elements (i.e., transient inattention and unexpected event) varied depending on the severity of the SCE. An unexpected event was more likely to be present in near-crashes (74%) compared to crashes (25%), while the opposite was true for transient inattention near-crashes (28%) and crashes (43%). This trend in the results makes intuitive sense and replicates the findings of Phase I of the Crash Trifecta Study (Dunn et al., 2014). A direct comparison between the Phase I results and the findings of the current study was not possible due to differences in the data and a slight change in the coding of the unexpected event variable; however, the pattern of results across the two studies is similar. Both studies found transient inattention to be more prevalent in crashes compared to near-crashes. The most compelling explanation for this finding is that the presence of transient inattention means that drivers cannot react as quickly to the imminent threat, and are therefore less likely to make a successful evasive maneuver, which subsequently results in a crash rather than a near-crash.

As outlined by Victor et al. (2014), many crashes occur due to a combination of short glances (i.e., transient inattention) and a high situational change rate (i.e., unexpected traffic event). Glances do not necessarily have to be long to result in a crash; short glances combined with a rapidly changing situation can also lead to crashes. Surprisingly, this was not reflected in the results of the current study. A relatively small percentage of crashes and near-crashes were attributed to a combination of transient inattention (2.5%) and an unexpected event (7%). This difference may be due to the metrics used to determine transient inattention in the current study. There are multiple different measures of glance behavior that may result in a different outcome when paired with an unexpected event. Other measures include total eyes off forward road time, length of the longest glance, timing and duration of the last glance, and mean glance time. Further analysis of the SHRP 2 NDS data set used in the current study could examine these different eye glance metrics to determine their usefulness and potential contribution to the crash trifecta model.

The increased number of SCEs in the current study compared to those in Phase I meant the data set could be broken down by incident type for a more in-depth assessment of the applicability of the crash trifecta model. Of the 16 different incident types, the most common crashes were animal related, rear end (striking), rear end (struck), and road departure (left or right). The most common near-crashes were animal related, rear end (striking), sideswipe (same direction), and turn into path (same direction). A number of crash and near-crash types had very low counts, and thus could not be further analyzed (e.g., pedalcyclist and pedestrian related crashes). The majority of different types of near-crashes tended to be associated with pedestrians, animals, pedalcyclists, or other vehicles behaving unexpectedly. The presence of transient inattention in a number of incident types resulted in a higher proportion of crashes than near-crashes. For instance, just under 33% of rear end (striking) near-crashes were attributed to transient inattention, either individually or in combination with other crash trifecta elements. Over 50% of rear end (striking) crashes, on the other hand, were attributed to transient attention. Similarly, just under 25% of turn into path (same direction) near-crashes, compared to over 40% of crashes, were attributed to transient inattention, either alone or combined with other elements. Clearly, the presence of transient inattention increases the chances of an adverse event, resulting in a crash under some, but not all, circumstances.

Surprisingly, the crash trifecta model had limited explanatory value for the majority of the different incident types. Rear end (striking) and turn into path (same direction) had the highest proportion of crashes attributed to the crash trifecta (approximately 25% each), whereas pedestrian-related had the highest proportion of near-crashes associated with the crash trifecta. The crash trifecta was most applicable to at-fault (28%) and severe at-fault (32%) rear end (striking) crashes. The example given earlier in Figure 1 is a perfect illustration of this scenario, showing the contribution of all three crash trifecta elements to the ensuing crash.

As was the case in Phase I, the results of the current Phase II study suggest that assigning a single, unitary critical reason as the proximal cause of the SCE without considering additional contributing factors is likely to be a limitation that does not address the complexities involved in the genesis of a crash. Assigning a critical reason may be suitable for lower-severity SCEs, but when investigating higher-severity SCEs, the convergence of multiple elements needs to be recognized to adequately represent the complexities involved in the origins and formation of a crash event. Improvements to traditional crash reporting methods to account for these additional elements could include further training for police officers and/or crash investigators attending the scene of a crash. Also, the standard crash reporting form used by police could be changed to allow for additional elements to be added, rather than just reporting a single critical reason. Moreover, the crash trifecta concept may be able to assist researchers in determining why a crash occurred in one situation compared with a similar situation that resulted in a successful avoidance maneuver (i.e., a near-crash). The crash trifecta concept may also be helpful in identifying crash mitigation measures, particularly since the two most prevalent crash trifecta elements—unsafe driving behavior and transient driver inattention—are largely under the driver's control

LIMITATIONS

Despite the increased number of SCEs in the current study, over 80% of the Phase II crashes were either low-risk tire strikes or minor crashes. As mentioned earlier, low-risk tire strikes were excluded from the analyses; however, minor crashes make up the vast majority (approximately 70%) of the remaining crashes in the data set. While minor crashes are still crashes by definition, and have an increased risk element compared to low-risk tire strikes, there may be a difference between minor crashes and more severe or police-reportable crashes. Unfortunately, despite the increased size of the current data set, there was still only a relatively small proportion of crashes that were deemed to be severe or police-reportable, and thus an in-depth analysis examining the possible differences between these and more minor crashes was not possible. There is evidence to suggest that near-crashes can be used as a surrogate for crashes (e.g., Guo et al., 2010) but the results of the current study provide fairly consistent evidence of differences between the crash trifecta elements that contribute to crashes versus near-crashes.

While an effort was made to reduce the subjective interpretation of the unexpected event variable, data analysts were still ultimately required to make a judgment call on whether an event was unexpected and random. The definition of an unexpected event was narrowed from Phase I to try and eliminate the subjectivity as much as possible and over 95% of the events were double checked by a second data analyst; however, there is a possibility that two people might still misread or misinterpret an event. The most significant change in data reduction from Phase I was the requirement for the event to be truly unexpected or random. If the SV driver made an error based on an assumption about what another vehicle would do, that did not qualify as an unexpected event. For instance, if the SV changed lanes without checking his blind spot and there was another vehicle there, the event did not qualify as unexpected. Clearly, the SV driver did not expect the event, as we can assume that the lane change would not have occurred if the presence of another vehicle were known. However, the key point is that the *other* vehicle (i.e., V2) did not do anything unexpected. If both the SV and V2 attempted to move into the center lane at the same time, then that would be classified as an unexpected event. Essentially, if V2 was driving normally and did not do anything unexpected, then the event would most likely be due to the SV driver making an error or assumption about V2's actions. This distinction was conveyed to data analysts prior to the reduction process and the inter-rater reliability estimates were high; however, analysts were ultimately making a judgment call based on information available to them, so errors may still have occurred.

The current study only looked at the presence of crash trifecta elements in SCEs, such as crashes of varying severity and near-crashes. It did not incorporate an analysis of any baseline driving, which would be an equivalent period of time when a SCE did not occur, so it is not possible to examine the prevalence of the crash trifecta elements when drivers are not in a crash or near-crash. Therefore, it is conceivable that the crash trifecta elements occur frequently in everyday driving, and not necessarily just in crashes and near-crashes. Future research investigating the crash trifecta concept needs to incorporate an analysis of baseline driving, not just SCEs.

The development of in-vehicle driver-monitoring technologies may eliminate some of the need for subjective interpretation of NDS video data in the future. For example, speed- and headway-monitoring devices and lane departure systems could provide objective measures of unsafe driving behavior. Similarly, an accurate eye-tracking device would remove the need for data analysts to review and code the eye-glance data used to assess the presence of transient driver inattention. In regard to the unexpected event variable, crash avoidance technologies may assist in mitigating the impact of unexpected events while driving (e.g., by detecting roadside objects or pedestrians, or braking if the vehicle in front brakes suddenly). However, there would be instances when these technologies would not be sufficient to avoid an SCE, in which case a crash could occur.

APPENDIX A: INCIDENT TYPE DESCRIPTIONS AND CONFIGURATION

Incident Type	Category Definition	Examples and Hints
Animal-Related	Subject vehicle makes contact or nearly makes contact with any type of living animal which is on a trafficway or on a sidewalk or path contiguous with a trafficway.	
Backing into Traffic	Vehicle backs into traffic flow	
Backing (fixed object)	Vehicle backs into a non-moving, fixed object	
Opposite Direction (head-on or sideswipe)	Subject vehicle (V1) and other vehicle (V2) make or nearly make contact when the vehicles were traveling in opposite directions. Point of impact is/would have been front plane of both vehicles.	
Other	Interaction with any non-motorist conveyance, non-motorist, or motorist not included in the other categories.	Non-motorist conveyance includes baby carriage, coaster wagon, ice skates, roller skates, push cart, scooter, skate board, skis, sled, wheel chair, rickshaw, etc. Non-motorist includes persons riding on an animal or animal-powered conveyance and any person outside a sidewalk or path contiguous with a trafficway. This category also includes incidents involving dead animals and objects in the roadway.
Pedal Cyclist-Related	Interaction with a person on any type of self-propelled pedaled cycle, as either the driver or the passenger, which is on a trafficway or on a sidewalk or path contiguous with a trafficway including bicycles, tricycles, and unicycles. Also include pedal cyclists who hold onto a motor vehicle in motion.	

Incident Type	Category Definition	Examples and Hints
Pedestrian-Related	Subject vehicle makes contact or nearly makes contact with a pedestrian. A pedestrian is any person who is on a trafficway or a sidewalk/path contiguous with a trafficway, and who is not in or on either a motorized or non-motorized conveyance. Also includes persons who are in contact with the ground, roadway, etc., but who are holding onto a vehicle. This includes pedestrians who are entering/exiting a vehicle.	A non-motorist conveyance is a human-powered device by which a person may move or may move another person (e.g., baby carriage, wagon, ice/roller skates, push cart, scooter, skate board, skis, sled, wheel chair, rickshaw, but does NOT include pedal cyclists). Any of these examples should be coded as "Other".
Rear-End (striking)	Subject vehicle (V1) makes contact or nearly makes contact with any portion of the back of the vehicle in front (V2). Point of impact is or would have been the back plane of the lead vehicle (V2).	See Figure 2
Rear-End (struck)	Vehicle behind (V2) makes contact or nearly makes contact with any portion of the back of the Subject vehicle (V1). Point of impact is or would have been the back plane of the Subject vehicle (V1).	See Figure 2
Road Departure (end)	Any tire on the subject vehicle leaves the end of the roadway.	See Figure 2
Road Departure (left or right)	Any tire on the subject vehicle leaves the roadway, beyond the shoulder or onto median, on the left or right side of the roadway. Includes interaction with roadside barriers and curbs.	See Figure 2
Sideswipe (same direction)	Subject vehicle (V1) is struck or nearly struck by another vehicle (V2) or strikes or nearly strikes another vehicle (V2) on either the driver or passenger side of the vehicle (V1 or V2) when the vehicles were traveling in the	See Figure 2

Incident Type	Category Definition	Examples and Hints
	same direction. Point of impact is or would have been the side plane of either vehicle.	
Straight Crossing Path	Vehicle (Subject or V2) crosses another vehicle path perpendicularly. Both vehicles intending to proceed straight across each other's paths.	See Figure 2
Turn Across Path	Vehicle (Subject or V2) crosses in front of the path of another vehicle. Vehicles were initially on the same roadway, either in the same or opposite directions. Vehicle turning across path intends to turn right or left onto another trafficway and drove in front of the other vehicle.	See Figure 2. Should be reserved only for crashes/near-crashes that occur in intersections (not, for example, in parking lots)—Incident Type "Other" should be used otherwise
Turn into Path (opposite direction)	Vehicle (Subject or V2) turns into the path of another vehicle. Vehicles were initially on different trafficways, traveling perpendicular to each other. One vehicle turns into the path of the other vehicle, intending to be in the same lane or trafficway as the other vehicle but traveling in the opposite direction.	See Figure 2. Should be reserved only for crashes/near-crashes that occur in intersections (not, for example, in parking lots)—Incident Type "Other" should be used otherwise.
Turn into Path (same direction)	Vehicle (Subject or V2) turns into the path of another vehicle. Vehicles were initially on different trafficways traveling perpendicular to each other. One vehicle turns into the path of the other vehicle, intending to be on the same roadway and traveling in the same direction.	See Figure 2. Should be reserved only for crashes/near-crashes that occur in intersections (not, for example, in parking lots, which would be "Other".

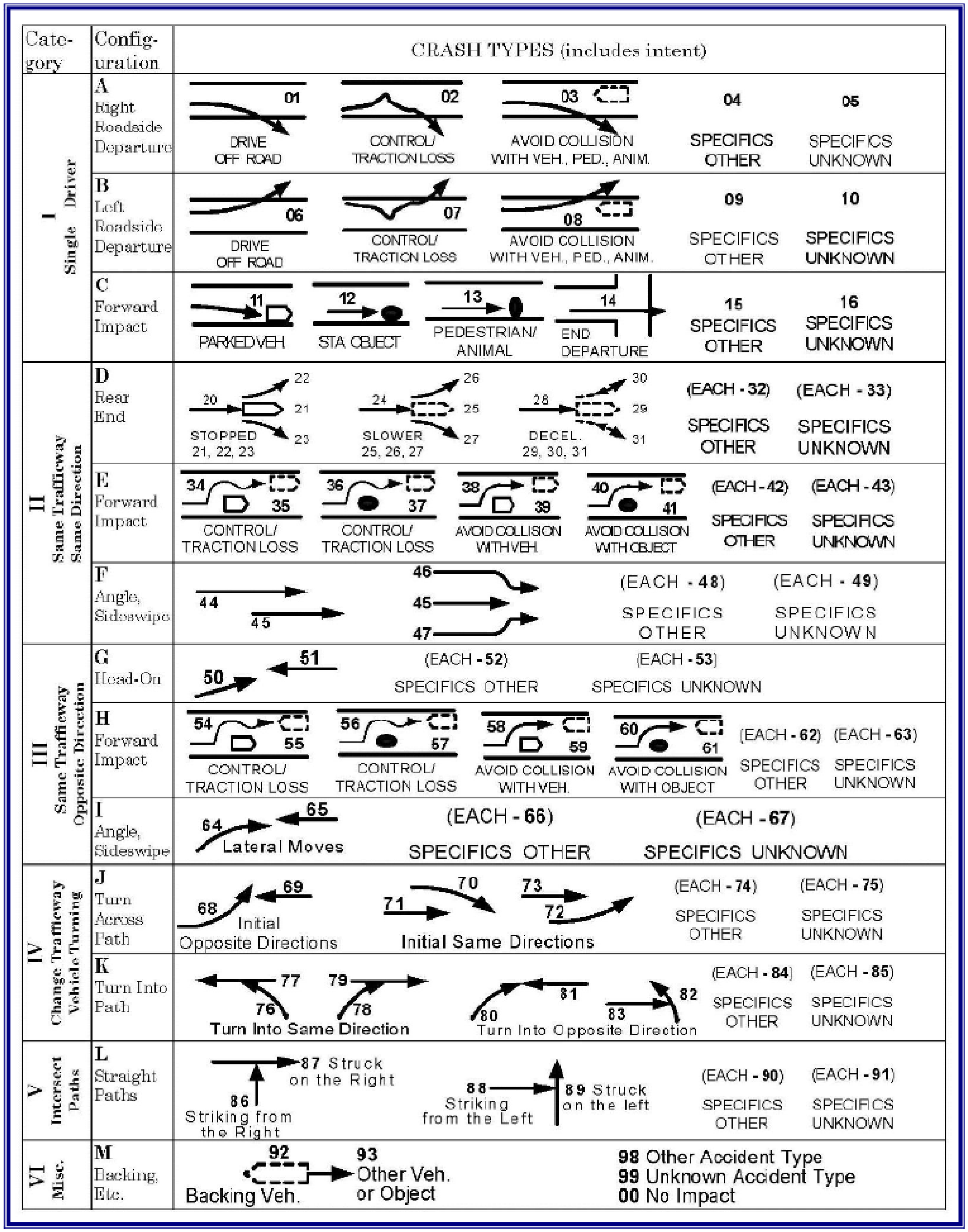

Figure 2. Graphic illustration. Vehicle configurations for the Incident Type variable.

APPENDIX B: UNSAFE DRIVING BEHAVIORS

Driver Behavior Category	Category Definition
Distracted	Subject vehicle driver is not maintaining acceptable attention to the driving task due to engagement in one or more secondary tasks.
Drowsy, sleepy, asleep, fatigued	Subject vehicle driver exhibits obvious signs of being asleep or tired, or is actually asleep while driving, degrading performance of the driving task.
Lane drifting	Subject vehicle driver fails to maintain appropriate and safe lane position and unintentionally drifts towards and/or over one or more lane lines.
Exceeded speed limit	Subject vehicle traveling at a speed greater than the posted speed limit (not in a work zone). In Variable Speed Zones, this is relative to the speed limit in effect at the time of the event. E.g., ≥ 10 mph above posted speed limit.
Exceeded safe speed but not speed limit	Subject vehicle traveling at a speed close to or under the posted speed limit, but still too fast to maintain a safe driving environment given current environmental conditions (e.g., weather, traffic, lighting). (Not in a work zone.)
Driving slowly: below speed limit	Subject vehicle traveling at a speed much lower than the posted speed limit when higher speeds are appropriate. E.g., ≥ 10 mph under posted speed limit.
Illegal passing	Subject vehicle passes another vehicle in an unsafe or illegal manner (other than on the right). E.g., passing across double line, going straight through turn lane, using shoulder.
Passing on right	Subject vehicle deliberately passes another vehicle in the lane (or shoulder, etc.) immediately to the right of the other vehicle. Includes moving into exit lane to pass a vehicle on the right and then re-entering roadway ahead of that vehicle, or passing a vehicle in an area not intended for traffic.
Other improper or unsafe passing	Subject vehicle passes another vehicle in an improper manner not included in previous categories. E.g., passing on two-lane road with limited sight distance or other vehicle present.

Driver Behavior Category	Category Definition
Cutting in, too close in front of other vehicle	Subject vehicle enters lane of another vehicle too closely to the front of that vehicle.
Cutting in at safe distance but then decelerated, causing conflict	Subject vehicle enters lane in front of another vehicle at a seemingly safe distance, but then decelerated inappropriately, causing a conflict. E.g., Subject moves into right lane at last minute to turn into parking lot and following vehicle not expecting the deceleration.
Cutting in, too close behind other vehicle	Subject vehicle enters lane of another vehicle too closely to the back of that vehicle.
Did not see other vehicle during lane change or merge	Subject vehicle enters a lane or merges into a lane without being aware of another vehicle close by that is already traveling in that lane.
Other improper or unsafe merge/exit/weave	Subject vehicle executes an improper transition between a through road and exit/entrance ramp or acceleration/deceleration lanes (or vice versa) or when a lane is dropped and two lanes are forced into one, and the error is not described in other options. E.g., inappropriately stopping at the end of an entrance ramp (with no yield sign), driving on shoulder to pass merging/weaving traffic, merging out of turn (before lead vehicle), merging without sufficient gap, moving into exit lane and then back out with insufficient warning.
Other improper or unsafe lane change	Subject vehicle executes an improper transition between two adjacent lanes when not in an interchange or lane drop situation, and the error is not described in other options. E.g., inappropriately moving into a third lane while changing between two (e.g. a "wide" lane change), changing lanes at an inappropriate time, or moving across multiple lanes in one maneuver.
Driving in other vehicle's blind zone	Subject vehicle is traveling close to another vehicle in such a way that the driver of the other vehicle is not expected to be able to see it. Subject vehicle must maintain this relative position for at least 5 seconds.
Aggressive driving, specific, directed menacing actions	Subject vehicle driver is driving in a purposefully aggressive manner, with actions intended for a specific recipient. E.g., exhibiting road rage.

Driver Behavior Category	Category Definition
Aggressive driving, other	Driver is driving in an aggressive manner not described in previous categories. Includes reckless and "sporty" driving. E.g., reckless driving without directed menacing actions, such as excessive speed, weaving in and out of traffic, tailgating.
Wrong side of road, not overtaking	Subject vehicle is traveling on the wrong side of the road with no intent of passing or overtaking another vehicle.
Following too closely	Subject vehicle is traveling at an unsafe distance (too close) behind the lead vehicle.
Failed to signal	Subject vehicle failed to properly signal its intent by not signaling at all. Applies to planned maneuvers, not sudden evasive maneuvers. E.g., changed lanes or made a turn without signaling.
Improper signal	Subject vehicle failed to properly signal its intent by signaling incorrectly or signaling late. Use with planned maneuvers, not sudden evasive maneuvers. E.g., used right turn signal when making a left turn, or activated turn signal at same time began maneuver.
Making turn from wrong lane	Subject vehicle turns left or right from a lane not intended for making that turn. E.g., making turn across lanes.
Improper turn, wide right turn	Subject vehicle turned right from the initial travel path, unnecessarily encroaching into the left adjacent lane or median. E.g., turning into oncoming traffic, turning into wrong lane on left.
Improper turn, cut corner on right turn	Subject vehicle turned right from the initial travel path, unnecessarily encroaching into the right adjacent lane or shoulder/curb. E.g., turning into wrong lane on right, or going over curb.
Improper turn, wide left turn	Subject vehicle turned left from the initial travel path, unnecessarily encroaching into the right adjacent lane or shoulder/curb. E.g., turning into wrong lane on right or going over curb.

Driver Behavior Category	Category Definition
Improper turn, cut corner on left	Subject vehicle turned left from the initial travel path, unnecessarily encroaching into the left adjacent lane or median. E.g., cuts into adjacent lane or oncoming traffic, turning into wrong lane on left or going over median.
Improper U-turn	Subject vehicle executes an improper U-turn, which may cause conflict with any direction of traffic and/or unintended road departures. E.g., making a U-turn where U-turns are prohibited, making a U-turn without yielding, making a U-turn with insufficient warning, making a U-turn with adequate space for vehicle's turning radius
Improper turn, other	Subject vehicle turned left or right from the initial travel path in an unsafe manner not described in previous categories.
Improper backing, did not see	Subject vehicle traveled in reverse without obtaining a proper view of the surroundings behind the vehicle. E.g., did not check mirrors when backing.
Improper backing, other	Subject vehicle traveled in reverse in an unsafe manner not described in previous categories. E.g., backing into traffic, backing up on interstate.
Improper start from parked position	Subject vehicle moved from a parked position in an unsafe manner. E.g., did not check mirrors.
Disregarded officer or watchman	Subject vehicle driver did not notice or obey an officer of the law or traffic guard serving to provide guidance in traffic flow and the driving task. E.g., unaware or late to react.
Signal violation, apparently did not see signal	Subject vehicle driver did not notice and thus disobeyed (or nearly disobeyed) a traffic signal. E.g., unaware or late to react.
Signal violation, intentionally disregarded signal	Subject vehicle driver saw a traffic signal but purposefully disregarded its instruction. (If driver was trying to beat a yellow light before it phased into red, code "Signal violation, tried to beat signal change".) E.g., driver saw a red traffic light but proceeded through the intersection, driver failed to stop before making a right on red.

Driver Behavior Category	Category Definition
Signal violation, tried to beat signal change	Subject vehicle driver accelerated or continued at a speed intended to pass through an intersection before the traffic signal turned red. E.g., went through (or attempted to go through) intersection while light was yellow.
Stop sign violation, apparently did not see stop sign	Subject vehicle driver did not notice and thus disobeyed or nearly disobeyed a stop sign. E.g., unaware or late to react.
Stop sign violation, intentionally ran stop sign at speed	Subject vehicle driver saw a stop sign but purposefully drove through the intersection at a speed greater than 15 mph. E.g., purposefully ran stop sign without decelerating below a speed of 15 mph.
Stop sign violation, "rolling stop"	Subject vehicle driver did not come to a complete stop at a stop sign (minimum speed was below 15 mph, but above 0 mph).
Other sign (e.g., Yield) violation, apparently did not see sign	Subject vehicle driver did not notice and thus disobeyed a traffic sign (other than a stop sign). E.g., Yield, Do Not Enter, One Way
Other sign (e.g., Yield) violation, intentionally disregarded	Subject vehicle Driver saw a traffic sign (other than a stop sign) but purposefully disobeyed that sign.
Other sign violation	Subject vehicle driver disobeyed a traffic sign in a manner not described in previous categories.
Non-signed crossing violation	Subject vehicle driver proceeded through a non-signed intersection in an unsafe manner. E.g., did not check traffic when entering roadway from driveway or parking lot.
Right-of-way error in relation to other vehicle or person, apparent recognition failure	Subject vehicle driver made the incorrect decision regarding who had the right-of-way (his/her own vehicle or another vehicle or pedestrian) due to a misunderstanding of the situation. E.g., did not see other vehicle.
Right-of-way error in relation to other vehicle or person, apparent decision failure	Driver made the incorrect decision regarding who had the right-of-way (his/her own vehicle or another vehicle or pedestrian) due to improper analysis of the situation. E.g., did see other vehicle prior to action but misjudged gap.

Driver Behavior Category	Category Definition
Right-of-way error in relation to other vehicle or person, other or unknown cause	Subject vehicle driver made incorrect decision regarding who had the right-of-way (his/her own vehicle or another vehicle or pedestrian) for an unknown reason or for reasons not described in previous categories.
Delayed or insufficient braking	Subject vehicle driver failed to brake, braked or decelerated later than was reasonably expected, or failed to brake or decelerate at a reasonably sufficient level given the circumstances of the event. Braking may or may not have led to a complete stop.
Sudden or improper braking	Subject vehicle braked suddenly, in an unsafe manner, or at an unsafe time in the roadway, but did not come to a complete stop (i.e., speed indicator did not drop to zero). This does not include delayed or insufficient braking.
Sudden or improper stopping	Subject vehicle stopped (speed indicator dropped to zero) without ample warning or in an unsafe manner or at an unsafe time in the roadway.
Parking in improper or dangerous location	Subject vehicle parked (stopped with the intent of remaining stopped) in a location not intended for parking. E.g., shoulder of Interstate
Speeding or other unsafe actions in work zone	Subject vehicle traveling at a speed greater than the posted speed limit, specifically while driving in a work zone.
Failure to dim headlights	Subject vehicle traveling with high beams activated on headlights, without dimming the lights when appropriate.
Driving without lights or with insufficient lights	Subject vehicle traveling with no headlights on (or insufficient headlights) when the situation requires such lighting for safety.
Apparent unfamiliarity with roadway	Subject vehicle driver behaved in an unsafe manner, apparently due to an unfamiliarity with the surrounding traffic situation or locality. E.g., repeated U-turns, reading maps, papers, etc.
Apparent unfamiliarity with vehicle	Subject vehicle driver behaved in an unsafe manner, apparently due to an unfamiliarity with the vehicle. E.g., unfamiliarity with displays and controls

Driver Behavior Category	Category Definition
Apparent general inexperience driving	Subject vehicle driver behaved in an unsafe manner, apparently due to lack of experience with the driving task. E.g., hyper-focused driving, overly cautious maneuvers, etc.
Use of cruise control contributed to late braking	Subject vehicle driver delayed applying brake pedal because the cruise control was activated, resulting in an unsafe situation.

APPENDIX C: UNEXPECTED EVENT DATA REDUCTION PROTOCOL

Protocol for Unexpected Event Reduction

The goal of this task is to review 10 seconds prior plus the event for crash, near crash events from SHRP 2 data collection, in order to identify any "unexpected events" in the window before the events occurs.

An unexpected event is defined as something random and unexpected that occurs in relation to the subject vehicle (i.e., our driver).

- ➢ Animal or pedestrian runs in front of car
- ➢ Debris hits vehicle
- ➢ Car pulls out in front of the vehicle or encroaches into subject's lane
- ➢ Car in front brakes suddenly
- ➢ Changes in traffic that happen while the subject is not paying attention (e.g., traffic moving freely, driver looks away and traffic stops)
    - o In regard to lack of attention, this does not include hitting stationary permanent objects that were visible the entire time (e.g., median strips, gutters, poles, etc.). Something needs to have changed in the scenario while they weren't paying attention for it to be considered "unexpected".

For this task, you will be reviewing crash, near crash events from SHRP 2 data collection using Hawkeye.

Setting up Hawkeye:

- ➢ Load Hawkeye
- ➢ Load the New SHRP 2 collection
- ➢ Load the following views/variables:
    - o Video (face, front, dash, rear)
    - o Speed
    - o You may save a layout it you wish for easier loading in the future.
- ➢ Open the "CrashTrifecta_AllSHRP 2.xlsx" spreadsheet located at \\vtti.ad.vt.edu\Data\Projects\449316\Reduction.
- ➢ Initial an event to indicate that you've signed it out to work on.
- ➢ Save

Open Event for Reduction:

- ➢ In Hawkeye, load the File ID.
- ➢ Select the Event you have signed out from the Select Event dialog box.
- ➢ Display the Event on the data charts by selecting the Overlay Enabled check box.

- You need to review the 10 seconds prior to the event (starting about 10 seconds into the epoch window) through the end of the event in order to determine if an unexpected event occurs at some point. An unexpected event could indicate movement by an object/vehicle/animal or an unexpected event due to lack of attention.

In the Excel file:

- Indicate if an unexpected event was present in the “Unexpected Traffic Event” column (Yes/No/Unable to determine/)
- Record your name and date you completed the review in the excel log for each event.
- Provide a brief description in the Notes/Questions column of the unexpected event if an unexpected event is observed (or a brief justification for why no unexpected event occurred).
- Save

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