Estimating Crash Consequences for Occupantless Automated Vehicles

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Acronyms

AOI	area of impact
BP	benefit parameter
CRSS	Crash Report Sampling System
FARS	Fatality Analysis Reporting System
GES	General Estimates System
IRB	Institutional Review Board
LPV	light passenger vehicle
LTK	light truck
LYL	life years lost
NASS	National Automotive Sampling System
NDS	naturalistic driving study
NHTS	National Household Travel Survey
NHTSA	National Highway Traffic Safety Administration
ODD	operational design domain
OV	occupantless vehicle
PC	passenger car
POV	principal other vehicle
SHRP 2	Second Strategic Highway Research Program
SV	subject vehicle

Executive Summary

Occupantless vehicles (OVs) are a proposed application of automated vehicle technology that would deliver goods from merchants to consumers with neither a driver nor passengers onboard. The purpose of this research was to understand and estimate how the increased presence of OVs in the United States fleet may influence crash risk and associated injuries and fatalities. This is of particular interest as OVs may replace some subset of the trips taken by U.S. drivers. OVs have unique physical characteristics that may be expected to improve road safety, such as low mass, the absence of human occupants, and lower structural rigidity requirements, and they operate within specific operational design domains (ODDs), including low-speed environments and locations with reduced exposure to crossing traffic.

The approach used to estimate potential modifications in crash risk consequences was a counterfactual simulation, where real-world observations were modified as if alternate events had occurred. This analysis leveraged several U.S. national crash databases, along with the Second Strategic Highway Research Program (SHRP 2) Naturalistic Driving Study (NDS) dataset. The results of this investigation are intended to inform future proposals to modify current safety standards, enact new standards, or define vehicle classifications that appropriately accommodate OVs.

This study assumes that driver behavior is constant across manually driven vehicles and their automated counterparts, focusing instead on the impact of changes to vehicle design. This assumption is motivated by a desire to make this study unique and to understand what safety benefits may arise from new classes of motor vehicles that are enabled by the emergence of autonomous driving systems. This core assumption disregards the consideration of an additional benefit that autonomous driving systems may offer: the reduction or elimination of human error and impairment as a causal crash factor.

National crash databases were downloaded, merged, curated, and stored in an in-house database system for ease of access and processing. The team also obtained access to the SHRP 2 NDS crash annotations. Relevant characteristics of the OV were defined, as were the confines of the ODD in which this vehicle was expected to operate. The counterfactual simulation work progressed in parallel and independently for both the national databases and the SHRP 2 NDS, with some occasional cross-pollination of information across databases occurring as needed.

The analysis required the derivation of parameters that could be used to modify existing crash estimates as OVs enter the fleet in greater numbers. These parameters were meant to indicate the likelihood that any particular crash event would have benefited from replacing the vehicular actors in the event with the model OV, as well as the degree of severity reduction that may be expected to be observed in such hypothetical situations. Ultimately, the team estimated benefit parameters pertaining to (1) the crashes that could be ultimately avoided altogether based on the OV's smaller size, (2) benefits that could be obtained from the improved crashworthiness characteristics of the OV, and (3) benefits due to the lack of occupants in the OV.

Of the 58,852 fatalities in the national databases examined, a full-scale market penetration of OVs was estimated to reduce fatalities by 34,284, a reduction of 58.2%. Most of this reduction (83%) would come from the lack of occupants in the OVs. Similarly, of the 6,615,117 injured persons in the national databases examined, a full-scale penetration of OVs was estimated to reduce injured persons by 4,088,935, a reduction of 61.8%. As was observed for fatalities, most of this reduction (72.1%) would come from the lack of occupants in the OVs.

The results of this investigation suggest that there is potential for OVs to reduce the number of fatalities and injured persons that occur on the nation's roadways. Most of that reduction will come from the removal of occupants who are simply making a trip to obtain goods that can be delivered by an OV. The extent of that reduction varies with respect to injured persons or fatalities, with a slightly larger proportion of injured persons than fatalities being avoided. The results of this investigation, however, should not be taken as definitive benefit estimates. There are important assumptions inherent in the parameters that were used, and some of these assumptions may not be immediately realized. Rather, the results are meant to support critical thinking into how innovative technologies such as OVs may offer benefits that transcend the typical approaches used in vehicle safety, including passive and active safety measures.

Introduction

Occupantless vehicles (OVs) are a proposed application of automated vehicle technology that would deliver goods from merchants to consumers with neither a driver nor passengers onboard. The purpose of the research presented in this report was to understand and estimate how an increased presence of OVs in the United States fleet might influence crash risk and associated injuries and fatalities, particularly as these vehicles replace some subset of the trips taken by U.S. drivers. OVs have unique characteristics such as low mass, absence of human occupants, and lower structural rigidity requirements, and operate within specific operational design domains (ODDs; e.g., reduced exposure to crossing traffic, low speeds). These characteristics and operational constraints are expected to reduce the overall risk that OVs contribute to the driving environment compared to their manually driven counterparts, particularly in terms of injuries and fatalities.

This study assumed that the driver behavior stays constant across manually driven vehicles and their automated counterparts, focusing instead on the impact associated with changes in vehicle design. This assumption was motivated by a desire to understand what safety benefits may arise from new classes of motor vehicles that are enabled by the emergence of autonomous driving systems. This core assumption disregards an additional benefit that autonomous driving systems may offer: the reduction or elimination of human error and impairment as a causal crash factor (Singh, 2015).

A counterfactual simulation, in which real-world observations were modified as if alternate events had occurred, was used to estimate the potential changes in crash risk. This approach is not novel in the area of traffic safety, having been implemented in a variety of contexts (Davis et al., 2011; McLaughlin et al., 2008; Sander, 2017; Bärgman et al., 2015; Lee, et al., 2018). In this case, real crashes from several national crash databases and the Second Strategic Highway Research Program (SHRP 2) Naturalistic Driving Study (NDS) dataset were systematically examined to determine the extent to which an OV could feasibly replace each of the actors in the event, and, if so, what potential benefits there could be in terms of crash prevention, fatality elimination, and reduction of injury severity.

The results of this investigation are intended to inform future proposals to modify current safety standards, enact new standards, or define vehicle classifications that appropriately accommodate OVs. These modifications are based on the expectation that the absence of human occupants, comparatively lower mass, and increased crash compatibility with a large array of other vehicles and other road users will make OVs a safe alternative to manually driven vehicles.

In addition to the counterfactual simulation, there was a parallel effort to further clarify and age-adjust the crash rates observed in the SHRP 2 NDS that occurred within the ODD of interest (based on the approach used by Blanco et al., 2016). The approach and results for the calculation of these rates are presented within Appendix B.

The work necessary to complete this investigation was funded by Nuro, who also provided support and feedback related to the analysis approach, counterfactual simulation parameters, and the findings summarized in this report.

Data Sources

Real-world U.S. crash data were used as the primary data sources in this investigation, including several datasets established and maintained by the National Highway Traffic Safety Administration (NHTSA). Specifically, three national crash datasets were used: the Fatality Analysis Reporting System (FARS), the National Automotive Sampling System's (NASS) General Estimates System (GES), and the Crash Report Sampling System (CRSS). CRSS replaced NASS GES in 2016.

FARS contains data on police-reported traffic crashes involving a motor vehicle traveling on a trafficway customarily open to the public and resulting in the death of at least one involved occupant or non-occupant within 30 days of the crash. The NASS GES and CRSS contain data from a sample of U.S. police-reported crashes involving all types of road users, of all crash severities ranging from property damage only to fatal. The national crash databases and associated documentation are posted annually by NHTSA; more detail is available at https://www.nhtsa.gov/crash-data-systems.

The findings from the national crash databases were complemented by the SHRP 2 NDS dataset, which includes vehicle kinematics and video for over 5.5 million trips taken by over 3,500 participants. The trips encompassed about 32 million miles of driving data collected during thousands of hours of vehicle operation and resulted in nearly 2,000 identified crash events ranging from minor to severe. The SHRP 2 NDS was conducted at six different sites across the United States. Some sites were primarily urban in nature and some were primarily rural. Data were collected from October 2010 through December 2013. Additional details about the SHRP 2 NDS can be found in Antin et al. (2019).

Method

The team obtained approval for this research from the Virginia Tech Institutional Review Board (IRB). The national crash databases are publicly accessible. These databases were downloaded, merged, curated, and stored in an in-house database system for ease of access and processing. Access to the SHRP 2 NDS was granted through a data use license for non-identifying data.

Characteristics of the OV were then defined, as were the confines of the ODD in which the OV is expected to operate. The counterfactual simulation work progressed in parallel and independently for both the national databases and the SHRP 2 NDS, with some occasional cross-pollination of information across databases occurring as needed. The rest of this section provides additional details on the counterfactual simulation used in this investigation.

OV Operating Characteristics and ODD

The characteristics used to define an OV included lack of occupants, smaller size, speed restrictions, crash compatibility features, and vehicle maneuverability and function.

As the name suggests, the primary characteristic of an OV is the lack of human occupants; rather than transporting passengers as in other automated driving applications, an OV delivers goods to customers. The obvious benefit of this is that there will never be occupants in the vehicle who can be harmed in the course of a crash. However, there will at times be occupants around the vehicle (e.g., customers collecting items from the vehicle), making pedestrian crash compatibility an important factor in this study.

OVs are also characterized by weight and bumper height. OVs weigh less than passenger trucks and most light vehicles in the current fleet. The bumper height is similar to that of a small coupe. These factors are relevant in any harm analysis since they influence a vehicle's crash compatibility (Monfort et al., 2019).

Assuming a height of 6.1 ft, an OV is taller than a sedan, similar in height to an SUV or pickup truck, and shorter than a large truck or van. However, at 8.8-ft long and 3.6-ft wide, the OV is significantly shorter and narrower than most other cars on the road. The reduced length and width may provide an OV with more space to avoid a safety-critical situation, such as an occluded pedestrian. Furthermore, because vehicle control algorithms do not have to consider passenger comfort in the OV, stopping distance may occasionally be less than that of vehicles containing occupants; however, this benefit was not included in the risk reduction calculations used in this analysis since it could not be readily quantified using current OV data.

Crash compatibility is also aided by the construction of the vehicle's top, which is mostly molded plastic with some small metal elements. Likewise, the front of the vehicle is designed as a crumple zone. In addition, the OV does not have an A-pillar, which helps to reduce head injuries for pedestrians in certain crash scenarios, and does not feature a hood, which can result in head injuries in pedestrian crashes involving manually driven light and heavy vehicles.

The ODD for the OV was constrained to roadways with posted speed limits at or below 45 mph. The limitation is a function of expected vehicle sensing, algorithmic, and actuation capabilities and of the expected functionality of the vehicle, which will deliver goods collected at local distribution centers to residential and business areas, which tend to be concentrated on roadways with speed limits at or below 45 mph. In addition, the vehicle was assumed to be capable of operating during day, night, and inclement weather conditions. The OV is not expected to replace large delivery vehicles (e.g., box trucks, tractor trailers).

National Crash Databases Event Selection and Processing

The initial step in using the national databases was to identify all vehicles involved in fatal crashes that fit the OV's ODD specification. Using calendar year 2013–2017 data from the FARS database, the vehicle data were filtered so that only model years 1997 or later were collected. This exclusion was performed so that only modern vehicle safety standards would be considered in the comparison to the OV. Next, the remaining vehicles were filtered to include only light passenger vehicles (LPVs; i.e., passenger cars and light trucks under 10,000 lbs. Gross Vehicle Weight Rating). The remaining data were then filtered to retain vehicles that were on a roadway with a speed limit less than or equal to 45 mph. Vehicles that were on interstate highways and ramps were also excluded at this stage to reduce the effect of unreliable speed limit data in subsequent analyses. As a result, 58,870 crashes involving 76,529 vehicles were retained for further analysis (Table 1). These crashes resulted in 23,760 non-motorist and motorcyclist fatalities, and 35,092 LPV occupant fatalities, for a total of 58,852 fatalities included in the subsequent analysis.

Table 1. Initial crash and vehicle selection in FARS.

	Crashes	Vehicles	Fatalities	
Total Number of Fatal Crashes (2013 - 2017)	161,791			
Total Number of Vehicles Involved in Fatal Crashes (2013 - 2017)		251,044		
Model years >= 1997		220,465		
& Light Passenger Vehicle (LPV)		174,655		
& Speed Limit <= 45mph		77,884		
& Not an Interstate Hwy		76,529	Vehicles of Interest	
Crashes of Interest	58,870			
Total Non-Motorist and Motorcycle fatalities			23,760	
Total LPV Occupant fatalities			35,092	
Total Fatalities in crashes with LPV meeting the ODD			58,852	

While FARS data are a census of fatal crashes, the GES/CRSS datasets contain a sample of all police-reported crashes. Therefore, a weighting factor must be applied to GES/CRSS crashes in order to obtain an unbiased estimate of the real-world crash frequencies. Accordingly, when results pertaining to GES/CRSS are discussed in this report, two numbers will be reported: the unweighted sample size and the corresponding weighted national estimate.

The same selection criteria were used with the GES/CRSS data as with the FARS data, but with one additional filter: fatal crashes were removed from the GES/CRSS data because these crashes were already represented in the FARS database analysis. As a result, there were 38,147 police-reported crashes that fit the ODD, representing 2,733,985 weighted crashes[1]. Similarly, there were 67,777 vehicles (unweighted) involved in these crashes, representing 5,030,091 weighted vehicles (Table 2). These crashes resulted in 498,184 injured non-motorist and motorcyclists, and 6,116,933 injured LPV occupants, for a total of 6,615,117 injured persons included in the subsequent analysis.

Table 2. Initial crash and vehicle selection in GES/CRSS.

	Crashes	Wcrashes	Vehicles	Wvehicles	Injured
Non-Fatal Police Reported Injury Crashes (2013 - 2017)	246,381	31,294,674			
Total Number of Vehicles Involved in These Crashes (2013 -			444,961	58,007,612	
Model years >= 1997			403,008	52,344,026	
& Light Passenger Vehicle (LPV)			367,241	48,811,767	
& Speed Limit <= 45mph			238,761	31,972,390	
& Not an Interstate Hwy			235,982	31,623,979	
& Remove Fatal Crashes			233,280	31,561,194	
& Remove Vehicles with No Injuries			67,777	5,030,091	
Crashes of Interest	38,147	2,733,985			
Total Injured Non-Motorists and Motorcyclists					498,184
Total injured LPV Occupants					6,116,933
Total Injured Persons in crashes with LPV meeting the ODD					6,615,117

The resulting vehicle-level data for FARS and GES/CRSS were then categorized based on OV-relevant attributes and ODD characteristics. Data fields used in this assessment included vehicle body type, crash type, first vehicle crash event, most harmful crash event, speed limit, area of impact, collision partner body type,

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[1] Refer to https://crashstats.nhtsa.dot.gov/Api/Public/ViewPublication/812706 for a detailed description of the derivation process for these weighting factors.

collision partner area of impact, and collision partner speed limit. For example, there were several crashes where the vehicle of interest was a parked vehicle. Since a parked vehicle is not moving and has no speed limit associated with it, the collision partner's speed limit was used. Several crashes were consequently eliminated due to the collision partner's speed limit exceeding 45 mph. Also, several crashes, where the most harmful event was "Fell/Jumped from Vehicle," were eliminated from further consideration since these were considered unique situations that would not be affected by an OV.

After filtering was completed at the vehicle level, the corresponding person-level data were examined. All persons in the vehicles of interest, non-motorists in collisions with the vehicles of interest, and persons on motorcycles (or vehicles of similar mass) involved in a crash with the vehicles of interest were identified. This allowed for the subsequent benefit calculation of associated outcome parameters and crash avoidance estimates, based on the 58,852 fatalities and 6,615,117 injured persons identified in FARS and GES/CRSS.

Uncertainties Using Real-world, Police-Reported Crash Data

As with any data created and entered by a human, there are inaccuracies in the police-reported national crash data. In general, FARS data tend to be quite reliable, mainly due to the severity of the event which generally prompts detailed investigation from the responding officer(s). However, fields such as *travel speed* are reported as estimates and are not regularly reported by many states, which produces some unquantifiable bias in the analysis of such fields. For non-fatal injury severity, the KABCO injury scale is reported (Association of Traffic Safety Information Professionals, 2018). While police officers report the best information they can, they are generally not medically trained, and the KABCO data can be imprecise. Furthermore, for this study, crash event details are needed to identify the OV's potential collision partners. Many crashes, particularly in FARS, are multi-vehicle or multi-event crashes. Considering the chaotic nature of a complex multi-vehicle, multi-event crash, accuracy in identifying the collision partners and order of events can be an issue. Because the most harmful event for the subject vehicle (SV) is a particular data element necessary for the proposed benefit calculations, and this depends on the precision of the KABCO scale by the reporting officer, accuracy becomes even more of a concern. Because of this uncertainty, a conservative approach was used in this analysis when calculating the estimated reductions in crash severity.

SHRP 2 NDS Event Selection and Processing

The Virginia Tech Transportation Institute (VTTI) classified the crash and near-crash events in the SHRP 2 NDS based on the extent that they matched the OV's ODD specifications. Therefore, only SHRP 2 NDS events occurring on roads with speed limits not exceeding 45 mph were considered. Other criteria, such as impact configuration, impact location, type of vehicle/object, and fault were then used to identify 1,681 crash events occurring within the prescribed ODD. This study did not consider near-crashes (i.e., avoided crashes that are often used as crash surrogates in safety analyses) because the data for near-crashes did not contain information that could be used to ascertain harm avoidance by an OV.

SHRP 2 NDS–Derived Benefit Calculations

Using the subset of applicable SHRP 2 NDS events, several harm-reduction metrics based on OV characteristics and the associated ODD were calculated for the crashes in the SHRP 2 NDS. These metrics included an indication of whether or not the SHRP 2 NDS crash-involved vehicles could have potentially been replaced by an OV, an estimate of the number of occupants in these vehicles, and whether or not there would be any benefit if a vulnerable road user were to be struck by an OV instead of a conventional vehicle.

Note, however, that only four SHRP 2 NDS crashes within the ODD involved a vehicle striking a vulnerable road user.
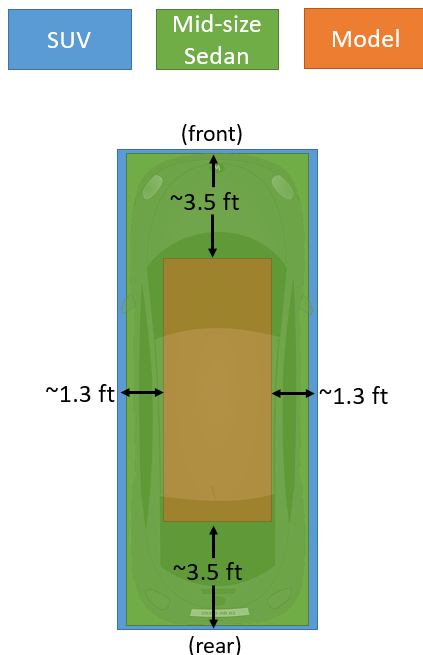
The crashes from the SHRP 2 NDS that occurred within the ODD specification (*n* = 1,681) were further examined to determine the likelihood that a crash may have been avoided altogether had one of the involved vehicles been replaced by an OV. Because the OV is considerably smaller than the average light passenger vehicle, it is conceivable that the additional lateral and/or longitudinal clearance could have permitted actual crash events to have been resolved without impact had one of the conflict partners been replaced. To conduct a benefit assessment based solely on the smaller size of the OV, other parameters were assumed to remain equal, including vehicle dynamics (e.g., speeds), driver behaviors (e.g., adherence to traffic laws, behaviors, reactions), vehicle footprint center point locations, vehicle capabilities (braking/steering/traction), and overall visibility. This is a novel approach and the first time, to the authors' knowledge, that the effect of vehicle width has been evaluated with respect to crash avoidance.

The first step in preparing for this assessment was to determine the magnitude of the vehicle size difference if the LPV involved in the SHRP 2 NDS crash were replaced by an OV. An "average occupied LPV" length and width were calculated as an "average of averages"; that is, an average SUV length and width and an average mid-sized sedan length and width were estimated based on several readily available online sources[2]. These figures were then averaged together for an "average occupied LPV" length and width. The size of the average occupied LPV was then compared to the expected dimensions of the OV to determine the additional clearance the OV provides. With this method, and assuming the vehicle center points stay in the same place, the model OV would provide approximately 3.5 feet of additional space in the front and rear compared to the average occupied LPV and approximately 1.3 feet of additional space on each side (Table 3, Figure 1).

Table 3. Calculation of additional longitudinal and lateral clearance provided by the model OV compared to the average occupied LPV.

Vehicle Type	Length	Width
Typical SUV	*192 in*	*78 in*
Typical Mid-sized Sedan	*186 in*	*72 in*
Average Occupied LPV	184 in	75 in
Model Occupantless	106 in	43.2 in
Additional Clearance	41.5 in, front and rear	15.9 in, each side

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[2] For example: https://anewwayforward.org/average-car-length/#:~:text=All%20of%20our%20Research%20indicates,every%20car%20is%20like%20this.

Figure 1. Comparison of vehicle footprint size between a typical SUV (blue), a typical mid-sized sedan (green), and the model OV (orange). The model vehicle provides an additional ~3.5 feet of space to the front and rear and ~1.3 feet of space on each side.

Once the size difference was determined, the next step in the assessment was to define the set of events. That process began with the 1,681 SHRP 2 NDS crashes that were considered part of the OV's ODD. This set of events had been further reduced prior to the vehicle size assessment to remove single-vehicle events (e.g., tire-only and curb strikes), events where video views critical to the assessment were missing, and events that occurred in inclement weather that prevented roadway features from being clearly visible (e.g., snow). In a few cases (*n* = 7), two subject-relevant crashes occurred within the same event; in these cases, both crashes were assessed independently. This resulted in a total of 499 SHRP 2 NDS events selected for further evaluation.

The videos for the remaining crashes were systematically reviewed to determine the likelihood of crash avoidance based on the lateral and longitudinal space clearance provided by the hypothetical substitution of the OV for either the SV or the principal other vehicle (POV). As such, each crash event was assessed once for replacing the SV (assuming that the POV remained the same) and once for the POV (assuming that the SV stayed the same). The only exceptions to this were crashes where the other conflict partner was a heavy commercial vehicle (e.g., tractor trailer, bus), a vulnerable road user (e.g., pedalcyclist, pedestrian), an animal, or an object. In these cases, the only hypothetical vehicle substitution assessed was for the SV.

For each hypothetical vehicle-replacement assessment, one of three outcome categories was subjectively assigned:

- Unchanged: 0% to 25% likelihood that the crash would have been avoided.
- Uncertain: 26% to 75% likelihood that the crash would have been avoided.
- Avoided: 76% to 100% likelihood that the crash would have been avoided.

A trained rater with over 5 years of experience assessing crash scenarios performed the ratings. All ratings were additionally reviewed by a senior researcher (who was also a member of the research team) for consistency and agreement. These assessments were highly subjective, but several guidelines were established to decrease subjectivity wherever possible. Vehicle speeds, directions of travel, and perceivable actual (but not potential) reactions were all taken into consideration. A stopping distance calculator[3] and a distance traveled calculator[4] were employed in many cases, along with metrics such as the speed at impact (since only the SV had a known speed, POV speeds were estimated) and where in the driver's reaction sequence the crash occurred (e.g., not yet reacting, movement to react, or active braking/steering), which had implications for the available driver reaction time. The rater used all information available to compare the space that would have been required to avoid the crash to the hypothetical space created by substituting the OV, all other things being equal. No assessment was made as to any potential change in severity of the observed crash due to hypothetical OV replacement; the assessment only considered whether the crash could have been avoided or not. Assessments of changes in severity were determined by the research team to be beyond the scope of the study and likely beyond the subjective, predictive capabilities available to the research team.

The results of this effort are discussed in detail later in the Results section; however, the outcome of the process was the creation of a "Potentially Avoided Crashes Due to Vehicle Size Differences" parameter, which was set at 4.8% for light trucks (LTKs) and 4.2% for passenger cars (PCs). The application of this parameter, as well as the derivation and application of other parameters, is discussed in the next section.

Derivation and Application of Outcome Severity Parameters

The analysis of the national databases required the derivation of parameters that could be used to modify the existing crash estimates as OVs enter the fleet in greater numbers. These parameters were meant to indicate the likelihood that any particular crash event would have benefited from replacing the vehicular actors in the event with an OV, as well as the degree of severity reduction that might be expected in such hypothetical situations.

First, the parameter derivation considered three primary categories for the crashes of interest: Vehicle vs. Non-Motorist, Vehicle vs. Motorcycles (or similar, e.g., mopeds), and Vehicle vs. Vehicle (when both vehicles were LPVs). These categories were derived based on existing conflict categories and differentiated based on the type of benefit expected and the magnitude of that benefit. In general, the benefits offered by substituting the OV as the collision partner were considered to be decreased likelihood of a crash due to smaller size; decreased risk of injury to other non-motorists, motorcycles, and vehicles due to increased crash compatibility features; and elimination of vehicle occupants.

Second, the effect of OVs was considered for two other categories of LPV crashes: Single Vehicle and Vehicle vs. Non-LPV (e.g., the collision partner was a heavy truck). For both categories, the primary benefit offered by the OV was considered to be the elimination of vehicle occupants.

The different crash categories evaluated are described in the rest of this section, along with the parameters that pertained to them and the process used for their derivation.

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[3] https://www.random-science-tools.com/physics/stopping-distance.htm
[4] https://www.calculatorsoup.com/calculators/math/speed-distance-time-calculator.php

Vehicles vs. Non-Motorists

For Vehicle vs. Non-Motorist crash events, non-motorists included occupants of a non-motor vehicle transport device, pedestrians, pedalcyclists, persons on personal conveyances, persons in/on buildings, and "unknown type" of non-motorist (i.e., uncategorized). Separate consideration of categories of collision partners is important because, given the lack of occupants, design requirements of the OV can be optimized towards providing improved pedestrian protection. These design features include smaller size, lower weight, sloping and collapsible front end, and lack of A-pillars, which can result in a reduction of hazard if the OV impacts a non-motorist.

The process of estimating an outcome severity parameter for non-motorists began with a review of the existing literature. Fifteen studies considering the impact of vehicle type on vulnerable road user injuries were individually reviewed (Ballesteros et al., 2003; Crandall et al., 2002; Desapriya et al., 2010; DiMaggio et al., 2006; Henary et al., 2003; Holland et al., 2000; Lane et al., 1994; Lefler et al., 2004; Margaritis et al., 2004; Matsui, 2005; Monfort et al., 2020; Nadler et al., 2001; Paulozzi, 2005; Pinkney et al., 2006; and Roudsari et al., 2004).[5] Specifically, VTTI was interested in the increased risk of fatal injury in vulnerable road user collisions with LTKs compared to conventional cars. The individual studies vary in applicability to this ODD, vary in the number of pedestrian fatality cases considered (from 55 in one study to over 4,800 in another), and contain point estimates ranging from a slight or no increase to a nearly 340% increase in fatal injuries for LTKs compared to conventional cars. Since the meta-analysis approach from Desapriya et al. (2010) was designed to "smooth" across several studies to avoid possible aberrations in any single study, and the results of the meta-analysis were encompassed within the extremes of the other papers, the meta-analysis became the primary result considered from the literature review. Desapriya et al. (2010) estimated a 54% larger risk of pedestrian fatality in collisions with LTKs compared to conventional cars.

To provide additional confirmation for the findings from the literature review and further understand the potential differences in pedestrian injury between a model OV and traditional vehicles, Nuro worked with researchers to simulate pedestrian collisions using a multi-body human body model and finite element vehicle models. Four pedestrian anthropometries were simulated (6YO, AF05, AM50, AM95) on each of three vehicle models: 2014 Chevrolet Silverado, 2014 Honda Accord, and a prototype OV. Each pedestrian model was positioned in mid-gait on the centerline of each vehicle. For the purposes of this study, it was assumed that the pedestrian safety characteristics of the Accord represent an average PC and the Silverado represents an average LTK.

Predictions were made from each of these simulations about the probability of injuries throughout the body and compiled into a single whole-body injury metric (life years lost, or LYL; Kim et al., 2002). This metric includes both the loss of functional capacity due to disabling injuries as well as the probability of fatality. This approach goes beyond the UN GTR-9 and European New Car Assessment Programme approaches, which consider only head and lower-extremity injuries. The simulation results showed that the model OV caused less whole-body injury than the LTK and PC models (Table 4).

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[5] Ballesteros et al. (2003), DiMaggio et al. (2006), Henary et al. (2003), Holland et al. (2000), Lane et al. (1994), Lefler et al. (2004), Margaritis et al. (2004), Nadler et al. (2001), Paulozzi (2005), Pinkney et al. (2006), and Roudsari et al. (2004) are included within the Desapriya et al. (2010) meta-analysis.

Table 4. Estimated non-motorist benefits in LYL based on crash event simulations.

	25 mph	15 mph
OV vs. LTK	23%	28%
OV vs. PC	3%	17%

These results are a conservative estimate of the potential for improved pedestrian protection from OV designs. The findings come from a prototype OV; therefore, the results do not necessarily consider all potential improvements and optimizations that may be possible as OV design matures. Furthermore, the crash was modeled on the vehicle centerline, which does not factor the potential benefits of avoiding A-pillar impacts. The estimates have several important limitations that could increase or decrease the benefits: (1) pedestrian sizes between the four anthropometries were not considered; (2) only two speeds were modeled; and (3) the results are based on modeling rather than physical crash tests. In addition, LYL as a metric is used cautiously, as it does not always offer appropriate equivalence between fatality and injury or consider the disparities that may be present in fatality and injury rates.

Given these limitations and considering the survey of the literature combined with the crash models, a conservative estimate for the vehicle vs. non-motorist benefit will assume that the harm from conflicts between the OV will be comparable to that of a passenger car; therefore, 0% reduction was applied. However, when the OV replaces an LTK, a 20% benefit was assumed (slight rounding down of the calculated 23% benefit at 25 mph in LYL).

Vehicles vs. Motorcycles (or Similar)

Using the logic that a motorcyclist is as vulnerable as a pedestrian when colliding with another vehicle, the same severity outcome parameter of 20% reduction was used when the OV replaced an LTK that struck a rider. Note that the Motorcycle category includes other motorized vehicles of similar mass with little or no occupant protection (e.g., mopeds, golf carts, ATVs).

Vehicles vs. Vehicles

In vehicle-to-vehicle crashes, it was assumed that one vehicle (the SV, an LPV in the ODD) at a time would be replaced by an OV, while the other vehicle was unchanged. Therefore, two benefit impacts were evaluated: the reduction in harm due to the SV being replaced by a smaller, lighter OV, and the reduction in risk to the occupants of the SV because, by definition, occupants are not present in an OV.

Vehicle Replacement

Two primary crash features were of interest in the case of reduced injury potential based on an OV replacing the LPV: the size of the vehicles involved and the area of impact (AOI). If the vehicle of interest (SV) was a PC and its collision partner was another PC, no severity outcome differentiation pertaining to size or AOI was applied since it is conservatively assumed that the OV would be equivalent to the PC in this crash configuration. Similarly, if the SV was an LTK, no severity outcome differentiation pertaining to size or AOI was applied since LTKs were the largest vehicle category being considered in the analysis. If, however, the front of a PC was struck by the front of an LTK, a 48% severity outcome reduction was applied. If, instead, the

PC was struck in the side by the front of an LTK, a 65% reduction was applied (National Center for Statistics and Analysis, 2003).

These severity outcome parameters were derived from NHTSA's *2002 Annual Assessment of Motor Vehicle Crashes* (National Center for Statistics and Analysis, 2003). NHTSA indicates that in two-vehicle crashes between PCs and LTKs—where the striking vehicle was the LTK—the PC occupants were 3.3 times more likely to be fatally injured in a head-on collision, but 20.8 times more likely to be fatally injured in a similarly configured side impact. The 3.3-times severity increase can be transformed to indicate that replacing LTKs with PCs in frontal crashes would result in about 30% of the current level of severity outcome, reducing those outcomes by 70%. Similarly, the 20.8-times severity increase can be transformed to indicate that replacing LTKs with PCs in side impacts could yield about 5% of the current level of severity outcome, reducing those outcomes by 95%.

However, it is important to note that this is an older study. Many improvements in crash compatibility have occurred in portions of the United States LPV fleet since 2002. For example, improved geometric alignment of energy-absorbing structures and advancements in side structure have occurred, and the fleetwide penetration of side air bags has increased. Consequently, current severity outcomes for LTKs could be expected to be less than the 3.3 and 20.8 times cited in the 2002 study.

A 2019 Insurance Institute for Highway Safety (IIHS) study on vehicle compatibility provides similar ratios for 2001–2004 and for 2013–2016, roughly comparable time frames to the 2002 NHTSA assessment and the 2013–2017 crash data used in this study. Although there are some differences in the selection criteria in the IIHS study compared to the NHTSA assessment (e.g., IIHS selects newer vehicles during the time frame and considers only driver fatalities), the results from the IIHS study are used here as a general adjustment to the NHTSA assessment to account for the changes between the two time frames. However, the IIHS study does not distinguish front and side crashes and presents the results separately for pickups and SUVs. Therefore, the IIHS pickup and SUV rates were consolidated based on their relative frequency in each time frame of the study: 2.97 * 65% pickups + 1.83 * 35% SUVS = 2.6 for 2001 to 2004, and 2.59 * 51% pickups + 1.28 * 49% SUVs = 1.9 for 2013 to 2016. The overall decrease of 32% observed between the two time frames was applied as a general adjustment to the 2002 NHTSA assessment to yield 48% for the front reduction ((1-32%) * 70%) and 65% for the side reduction ((1-32%) * 95%) if an LTK were replaced with an OV.

Occupant Replacement

The benefit for occupant replacement in crashes due to lack of occupants was set to be 100% for the vehicle being replaced by the OV, and thus ~50% of the occupants in these vehicle-to-vehicle crashes (the final calculation leveraged the actual number of occupants, which was on average split almost equally between SV and CP). When any PC or LTK was replaced by the OV in the analysis, all fatal and injured occupants in that vehicle were assumed to benefit because they would not have been present during the crash.

Single Vehicle and Vehicles vs. Non-LPV

For single-vehicle crashes and LPV crashes with non-LPVs (e.g., heavy trucks), the potential benefit of the OV was the elimination of vehicle occupants. As was done in the vehicle vs. vehicle crash category, the benefit for lack of occupants for this category was set to be 100%.

Parameter Summary

The spreadsheets used in the national database benefit calculations were designed to allow changes to these parameters. This was done to accommodate any additional information that would indicate a change to any particular parameter is warranted, effectively allowing for further counterfactual simulations to be performed in the future.

The final set of benefit parameters is summarized in Table 5.

Table 5. Assumed benefit parameters for LTKs and PCs.

Benefit Parameters (BP)	Collision Partner	
	LTK	PC
LPV in ODD Replacement with OV	100%	100%
Potentially Avoided Crashes Due to Vehicle Size Differences	4.8%	4.2%
Potential Severity Reduction Due to Vehicle Size for Non-Motorist/Motorcycle	15%	0%
Potential Severity Reduction Due to Vehicle Size for Light Truck – Front-to-Front Impacts	48%	0%
Potential Severity Reduction Due to Vehicle Size for Light Truck – Side Impacts	65%	0%
Replacement with OV in Crashes Between Two LPVs in ODD	50%	50%

Application of Outcome Severity Parameters to National Crash Databases

The application of the outcome severity parameters differed based on the type of event being examined. The rest of this section presents the algorithms that were used to obtain the results of interest, broken down by database and type of crash. **The same algorithms were used for FARS and GES/CRSS.**

The starting point for these analyses were the **76,529 vehicles in fatal crashes** (FARS) that matched the ODD, along with the 31,561,194 vehicles in non-fatal crashes that matched the ODD (from the GES/CRSS police-reported crash database), of which **5,030,082 vehicles had at least one non-fatally injured occupant** in that vehicle (Table 1 and Table 2). There were 58,852 fatalities and an estimated 6,615,117 non-fatally injured persons in these crashes.

Non-Motorists

Step 1: Determine which vehicles in the national databases were involved in a crash that had at least one non-motorist involved. As a category, "non-motorists" includes pedestrians, pedalcyclists, persons on personal conveyances, persons in or on buildings, and "unknown type" of non-motorist (i.e., uncategorized).

Step 2: Using a variable that identifies which vehicle struck the non-motorist, identify if a vehicle that meets the ODD struck the non-motorist.

Step 3: Determine whether the striking vehicle was an LTK or a PC. If not, the vehicle is excluded from the analysis; no replacement with an OV is possible.

Step 4: Apply the corresponding "LPV in ODD Replacement with OV" parameter for the involved vehicle type.

Step 5: Apply the corresponding "Potentially Avoided Crashes Due to Vehicle Size Differences" parameter for the involved vehicle type.

Step 6: Apply the corresponding "Potential Severity Reduction Due to Vehicle Size Non-Motorist/Motorcycle" parameter for the involved vehicle type.

Example: FARS non-motorists struck by LTKs that meet the ODD.

Using:

Benefit Parameters (BP)	Collision Partner	
	LTK	PC
LPV in ODD Replacement with OV	100%	100%
Potentially Avoided Crashes Due to Vehicle Size Differences	4.8%	4.2%
Potential Severity Reduction Due to Vehicle Size for Non-Motorist/Motorcycle	20%	0%

There were 7,931 LTKs in these fatal crashes, resulting in 8,031 non-motorist fatalities. Applying the benefit parameters above produces an estimated 1,915 fatalities avoided, which is a 23.8% reduction.

$$\Big(8031 - \big((8031 * 100\%) * (1 - 4.8\%) * (1 - 20\%)\big)\Big) = 1915$$

Motorcycles

The algorithm for crashes involving LPVs operating within the ODD in collisions with "motorcycles" was identical to the approach used for non-motorists. The Motorcycles category includes motored cycles, mopeds, all-terrain vehicles, and all-terrain cycles.

Example: FARS motorcycles in collisions with LTKs that meet the ODD.

There were 3,661 LTKs in these fatal crashes, resulting in 3,698 motorcycle fatalities. Applying the benefit parameters above yields an estimated 882 fatalities avoided, which is a 23.8% reduction.

$$3698 - \big((3698 * 100\%) * (1 - 4.8\%) * (1 - 20\%)\big) = 882$$

Vehicle vs. Vehicle

These crashes involve PCs or LTKs that meet the ODD requirements and crash with another PC or LTK that meets the ODD requirements. The algorithm addresses the killed or injured occupants in the SV. One vehicle at a time was analyzed. If both vehicles had any killed or injured occupants, then each vehicle was included separately in the analysis as an SV. Four SV/collision partner combinations are possible: LTK vs. LTK, LTK vs. PC, PC vs. LTK, and PC vs. PC.

Step 1: Verify that the SV is a PC or LTK meeting the ODD requirements and note the body type of the vehicle.

Step 2: Verify that the collision partner is a PC or LTK meeting the ODD requirements and note the body type of the vehicle.

Step 3: Determine the AOI for the SV and the collision partner.

Step 4: For SV fatalities, apply the "Potentially Avoided Crashes Due to Vehicle Size Differences" parameter for the respective vehicle type.

Step 5: For the remaining SV fatalities, apply the "Replacement with OV in Crashes Between Two LPVs in ODD" parameter, and calculate the result as a benefit. This benefit represents the potential fatalities reduced by replacing the SV with an OV (and thereby removing the vehicle occupants). Steps 6 and 7 below are

subsequently applied <u>to the remaining SV fatalities</u> to account for benefits attained from replacement of the collision partner with an OV.

Step 6: For the remaining SV fatalities, apply the "Potential Severity Reduction Due to Vehicle Size Light Truck – Front-to-Front Impacts" parameter to the front-to-front crash fatalities **if the collision partner is an LTK**.

 Step 7: For the remaining SV fatalities, apply the "Potential Severity Reduction Due to Vehicle Size Light Truck – Side Impacts" parameter to the front-to-side crashes **if the collision partner is an LTK**.

Example: FARS – SV is a PC and the collision partner is an LTK.

Using:

Benefit Parameters (BP)	Collision Partner	
	LTK	PC
Replacement with OV in Crashes Between Two LPVs in ODD	50%	50%
Potential Severity Reduction Due to Vehicle Size for Light Truck – Front-to-Front Impacts	48%	0%
Potential Severity Reduction Due to Vehicle Size for Light Truck – Side Impacts	65%	0%
Potentially Avoided Crashes Due to Vehicle Size Differences	4.8%	4.2%

There were 7,868 PCs involved in fatal crashes with an LTK. There were 5,403 occupant fatalities in these vehicles: 1,939 fatalities in front-to-front crashes, 2,386 in front-to-side crashes, 317 in front-to-other crashes, and 761 in non-frontal crashes. From Step 4, the fatality reduction from crashes avoided is 5,403 * (4.8%) = 227. The 50% benefit due to replacement of the PC with an OV gives a fatality reduction calculated by (5,403 – 227) * (50%) = 2,588. Applying Steps 6 and 7 proportionally to the remaining 2,588 fatalities (5,403 – 227 – 2,588):

$$(2588 \: / \: 5403) * \left(\left(1939 * (1 - 48\%) \right) + \left(2386 * (1 - 65\%) \right) + 317 + 761 \right)$$

This calculation estimates a reduction of 1,399 fatalities. The sum of the crashes avoided plus the SV replacement plus the collision partner replacement is 227 + 2,588 + 1,399 fatalities, which is a 78% reduction.

Example: FARS – Both vehicles are PCs.

Using:

Benefit Parameters (BP)	Collision Partner	
	LTK	PC
Replacement with OV in Crashes Between Two LPVs in ODD	50%	50%
Potential Severity Reduction Due to Vehicle Size for Light Truck – Front-to-Front Impacts	48%	0%
Potential Severity Reduction Due to Vehicle Size for Light Truck – Side Impacts	65%	0%
Potentially Avoided Crashes Due to Vehicle Size Differences	4.8%	4.2%

There were 9,800 PCs as SVs for this type of crash and 4,007 occupant fatalities in these vehicles. From Step 4, the fatality reduction from crashes avoided is 4,007 * 4.2% = 168. The 50% replacement of the PC with an OV gives a fatality reduction of (4,007 – 168) * (50%) = 1,919 fatalities. Applying Steps 6 and 7 proportionally to the remaining 1,920 fatalities (4,007 – 168 – 1,919), there is no reduction because the collision partner is a PC and the "Potential Severity Reduction Due to Vehicle Size" parameters for both front-to-front and side impacts is 0%.

The sum of the fatality reduction from crashes avoided and SV replacement is 168 + 1,919 + 0 = 2,088, which is a 52.1% reduction.

Single Vehicle

A variety of single-vehicle crash configurations exist (Figure 2). These are often crashes where the vehicle goes off the road and strikes an object such as a tree or a pole. The benefit in this case comes from the lack of occupants in the vehicle if an OV replacement occurs.
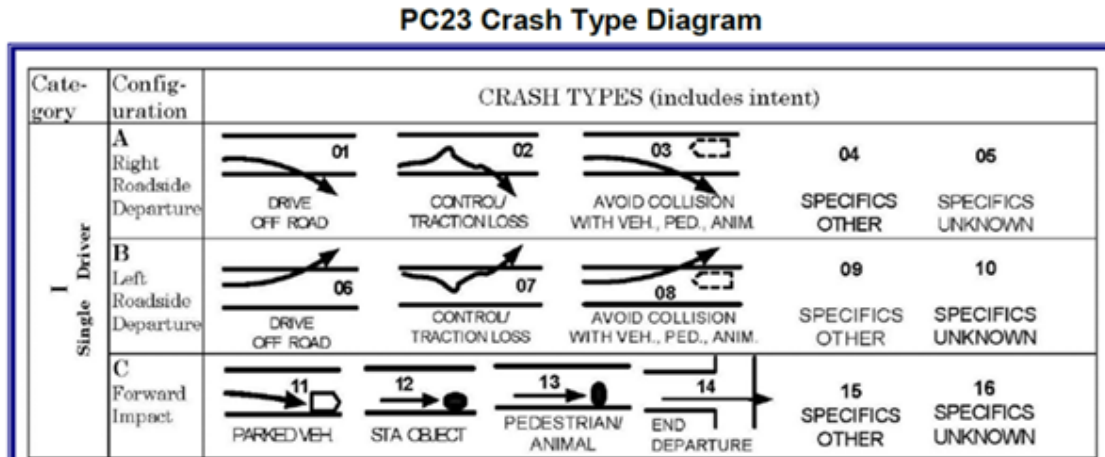
Figure 2. Crash type diagram for single-vehicle crashes.

Step 1: Verify that a vehicle meeting the ODD is involved in a single-vehicle crash based on its crash type and the lack of a collision partner. Note the body type of the vehicle.

 Step 2: Apply the 100% "LPV in ODD Replacement with OV" parameter for the respective vehicle type.

Example: FARS single-vehicle crashes involving an LTK operating within the ODD.

Using:

Benefit Parameters (BP)	Collision Partner	
	LTK	PC
LPV in ODD Replacement with OV	100%	100%

There were 16,176 LTKs in fatal single-vehicle crashes with 8,393 fatalities. The replacement of the LTK with an OV yields a 100.0% reduction of the 8,393 fatalities.

Vehicle vs. Other Vehicle

The algorithm for crashes involving Vehicles vs. Other Vehicle (i.e., atypical vehicle) is similar to that for single-vehicle crashes. The difference is that, in this case, the vehicle (an LPV that operates within the ODD) is involved in a crash with another vehicle that either is not an LPV (such as a medium/heavy duty truck or a motorcycle) or is an LPV not operating within the ODD. Motorcycles were analyzed separately above, but that analysis solely computed benefits for the passengers on the motorcycle if they were struck by an OV. This case examines the benefits for the occupants of the LPV in the ODD if it were replaced with an OV—that is, there would be no occupants in the vehicle considered in this case.

Step 1: Verify that an LPV operating within the ODD is involved in a crash with a vehicle from the "Other Vehicle" category.

Step 2: Apply the 100% "LPV in ODD Replacement with OV" parameter for the respective vehicle type.

Example: FARS Other Vehicle crashes for LTKs operating within the ODD.

Using:

Benefit Parameters (BP)	Collision Partner	
	LTK	**PC**
LPV in ODD Replacement with OV	100%	100%

There were 4,933 LTKs in fatal non-LPV crashes involving 1,045 fatalities. The replacement of the LTK with an OV yields a 100.0% reduction of the 1,045 fatalities.

Results

Effects of Vehicle Size on Crash Avoidance

The analysis of the effects of vehicle size on potential crash avoidance leveraged 499 SHRP 2 NDS crash events, mainly excluding single-vehicle events, events without the necessary videos, or events occurring in inclement weather that prevented roadway features from being clearly visible. Out of these 499 crash events, 7 cases had two subject-relevant crashes occurring within the same event. In those situations, both crashes were assessed independently, leading to a total of 506 crashes being assessed. Of these, 85 were Crash Severity Level I crashes, 141 were Crash Severity Level II, and 280 were Crash Severity Level III crashes (see definitions in Table 10 within Appendix A). Since each crash was assessed both from the perspective of the SV and the perspective of the POV, this resulted in potentially 1,012 hypothetical replacement cases. However, in 158 of these crashes, only the SV replacement case could actually be assessed because either there was no POV to substitute (e.g., the crash was with an object, animal, pedestrian, or bicycle) or because the POV was a heavy truck, which is not expected to be replaced by the OV. This yielded a final set of 854 hypothetical replacement cases.

The results allowed, for the first time, the quantification of reduced crash likelihood due to reduced vehicle width. In general, the assessment showed that some subsets of crash events had a higher likelihood than others of being avoided altogether through the involvement of a smaller vehicle (Table 6). As might be expected, the likelihood of the crash outcome being eliminated with the substitution of the OV was lowest for the most severe crashes (i.e., 2% avoided with SV substitutions, 4% avoided with POV substitutions) and highest for the least severe crashes (i.e., 22% for SV, 11% for POV). This is due in large part to the reduced speeds at which lower severity crashes typically occur, which more often would provide the additional stopping distance required to completely avoid a crash outcome.

Table 6. Effect of vehicle size on crash outcome results for SHRP 2 NDS crashes (Levels I, II, and III severity) when either the SV or POV is hypothetically replaced by the OV.

If SV = Occupantless	Level I		Level II		Level III		All Levels	
	#	%	#	%	#	%	#	%
# Cases (assessed)	85		141		280		506	
# Cases avoided	2	2%	6	4%	61	22%	69	14%
# Cases uncertain	8	9%	30	21%	72	26%	110	22%
# Cases unchanged	75	88%	105	74%	147	53%	327	65%
If POV = Occupantless	Level I		Level II		Level III		All Levels	
	#	%	#	%	#	%		
# Cases (assessed)	69		125		154		348	
# Cases avoided	3	4%	7	6%	32	21%	42	12%
# Cases uncertain	6	9%	24	19%	43	28%	73	21%
# Cases unchanged	60	87%	94	75%	79	51%	233	67%
All Cases	Level I		Level II		Level III		All Levels	
	#	%	#	%	#	%		
# Cases (assessed)	154		266		434		854	
# Cases avoided	5	3%	13	5%	93	21%	111	13%
# Cases uncertain	14	9%	54	20%	115	26%	183	21%
# Cases unchanged	135	88%	199	74%	226	52%	560	66%

The vehicle size effect results were further broken down by event types, including rear-end, sideswipe, intersection, opposite direction/head-on, backing, single vehicle, and bicycle/pedestrian. However, this breakdown yielded subsets of events that were often too small to justify making any generalizations. For the interested reader, however, the tables are included as Appendix A of this report. The calculation of benefits was accomplished by combining the subjective certainty of avoidance (e.g., over 75% for "cases avoided," 25% to 75% for "cases uncertain") and the resulting avoidance percentage. For example, that combination (75% * 13% + 25% * 21%) yields an overall 15% avoidance estimate when all crashes are considered. Note

that the selection of the lower limits for each range (e.g., 0% for less than 25% certainty, 25% for certainty between 25% and 75%) used in this calculation generates a conservative estimate for this parameter.

The aggregate figures in Table 6 for NDS Level I crashes (i.e., crashes resulting in injury, airbag deployment, or vehicle towing) were used for the subsequent calculation of benefits in the national crash databases. These crashes were the closest analog within the SHRP 2 NDS to the national crashes involving fatalities and injured persons. The calculation of benefits combined the subjective certainty of avoidance and the resulting avoidance percentage to yield 4.5% avoidance (75% * 3% + 25% * 9%) for LTKs and PCs in Level I crashes.

Because the number of Level I cases avoided is not sufficient to provide individual results for LTKs and PCs, the aggregate avoidance percentage was adjusted as follows. Because LTKs are generally longer and wider than PCs, the avoidance percentage was increased for LTKs and decreased for PCs proportionally to the difference in area (i.e., length * width) for the typical SUV and mid-sized sedan from Table 3. The ratio of the SUV/PC area is 1.118 (192 * 78 / 186 * 72), so the average SUV has an 11.8% larger area than a mid-sized sedan. The 4.5% avoidance percentage was increased by 5.9% (½ of 11.8%) for LTKs and decreased by 5.9% (½ of 11.8%) for PCs, reflecting the generally larger area of LTKs compared to PCs. Based on the roughly equal proportion of LTKs and PCs in the vehicle fleet, the resulting avoidance percentages of 4.8% for LTKs and 4.2% for PCs average to the overall 4.5% avoidance percentage observed in the SHRP 2 NDS crashes.

U.S. Crash Database Benefit Calculations

FARS – Fatal Crashes

From Table 1, there were 58,852 fatalities considered in the analysis, resulting from 58,870 crashes involving 76,529 LPVs meeting the ODD (note that some fatalities occurred in vehicles not considered for replacement). Given the benefit parameters, the estimation approach, and the number of fatal crashes occurring within the ODD, Table 7 summarizes the fatality reduction produced by the counterfactual simulation. Of the 58,852 fatalities, a large-scale market penetration of OVs would potentially reduce fatalities by 34,284 (58.3%). Most of this reduction (83.0%) would come from the lack of occupants in the OVs. Nearly 5% would come from avoided crashes.

Table 7. Summary of fatal crash potential benefits.

Benefit Parameters (BP)						Light Truck	Pass Car
LPV in ODD Replacement with Occupantless Vehicle (OV) (%)						100%	100%
Potentially Avoided Crashes Due to Vehicle Size Differences (%)						4.8%	4.2%
Potential Severity Reduction Due to Vehicle Size for Non-Motorist / Motorcycle (%)						20%	0%
Potential Severity Reduction Due to Vehicle Size for LPV - Front to Front Impacts (%)						48%	0%
Potential Severity Reduction Due to Vehicle Size for LPV - Side Impacts (%)						65%	0%
Replacement with OV in crashes between two LPV in ODD (%)						50%	50%

FARS - Fatal Crashes

Crash Type	Vehicle Body Type	LPV in ODD	Fatalities	Apply BP Avoided	Apply BP Occupantless	Apply BP replace CP	Reduction	% Reduction
Non-Motorist	**Collision Partner:**							
	LTK	7,931	8,031	385		1,529	1,915	23.8%
	PC	8,022	8,127	341		-	341	4.2%
	Total	15,953	16,158	727		1,529	2,256	14.0%
Motorcycles	**Collision Partner:**							
	LTK	3,661	3,698	178		704	882	23.8%
	PC	3,894	3,904	164		-	164	4.2%
	Total	7,555	7,602	341		704	1,046	13.8%
Vehicle* to Vehicle	**SV v CP:**							
	LTK v LTK	5,398	2,058	99	980	586	1,665	80.9%
	LTK v PC	8,051	1,277	61	608	-	669	52.4%
	PC v LTK	7,868	5,403	227	2,588	1,399	4,214	78.0%
	PC v PC	9,800	4,007	168	1,919	-	2,088	52.1%
	Total	31,117	12,745	555	6,095	1,986	8,636	67.8%
Single Vehicle	**Subject Vehicle:**							
	LTK	16,176	8,393		8,393		8,393	100.0%
	PC	18,611	11,174		11,174		11,174	100.0%
	Total	34,787	19,567		19,567		19,567	100.0%
Vehicle to Other**	**Subject Vehicle:**							
	LTK	4,933	1,045		1,045		1,045	100.0%
	PC	5,692	1,735		1,735		1,735	100.0%
	Total	10,625	2,780		2,780		2,780	100.0%
Total BP applied				1,624	28,442	4,219	34,284	
				4.7%	83.0%	12.3%		

Total LPV meeting the ODD	76,529		
Total Non-Motorist and Motorcycle fatalities		23,760	
Total LPV Occupant fatalities		35,092	
Total Fatalities in crashes with LPV meeting the ODD		58,852	

	Fatality Reduction
If non motorist collision with LPV replaced by Occupantless Vehicle	**2,256**
If motorcylist(s) collision with LPV replaced by Occupantless Vehicle	**1,046**
Subtotal: non-LPV occupants	**3,301**
If Light Vehicle replaced with Occupantless Vehicle in crashes with another Light Vehicle	**8,636**
If Light Vehicle replaced with Occupantless Vehicle in Single Vehicle Crashes	**19,567**
If Light Vehicle replaced with Occupantless Vehicle in Non LPV crashes	**2,780**
Subtotal: LPV occupants	**30,983**
Final Estimate	**34,284**

GES/CRSS - Non-Fatal Police-Reported Injury Crashes

Given the benefit parameters, the estimation approach, and the number of injury crashes occurring within the ODD, Table 8 summarizes the reduction in injured persons produced by the counterfactual simulations. Of the 6,615,117 injured persons in the databases examined, a large-scale market penetration of OVs would reduce the number of injured persons by 4,088,935 (61.8%), with 78.1% of this reduction being from avoided exposure to a crash, 72.1% from the lack of occupants in the OVs, and 6% from avoided crashes. The remaining 21.9% of the reduction in injured persons is from decreased injury in a case where the collision partner was an OV instead of an LTK.

Table 8. Summary of injury crash potential benefits.[6]

Benefit Parameters (BP)					Light Truck	Pass Car
LPV in ODD Replacement with Occupantless Vehicle (OV) (%)					100%	100%
Potentially Avoided Crashes Due to Vehicle Size Differences (%)					4.8%	4.2%
Potential Severity Reduction Due to Vehicle Size for Non-Motorist / Motorcycle (%)					20%	0%
Potential Severity Reduction Due to Vehicle Size for Light Truck - Front to Front Impacts (%)					48%	0%
Potential Severity Reduction Due to Vehicle Size for Light Truck - Side Impacts (%)					65%	0%
Replacement with OV in crashes between two LPV in ODD (%)					50%	50%

GES/CRSS - Non-Fatal Police Reported Injury Crashes

					Apply BP			
Crash Type	Vehicle Body Type	LPV in ODD	Injured Persons	Avoided	Occupantless	replace CP	Reduction	% Reduction
Non-Motorist	Collision Partner:							
	LTK	200,574	139,986	6,719		26,653	33,373	23.8%
	PC	136,217	206,816	8,686		-	8,686	4.2%
	Total	336,791	346,803	15,406		26,653	42,059	12.1%
Motorcycles	Collision Partner:							
	LTK	109,673	58,100	2,789		11,062	13,851	23.8%
	PC	77,644	93,282	3,918		-	3,918	4.2%
	Total	187,317	151,382	6,707		11,062	17,769	11.7%
Vehicle* to Vehicle	SV v CP:							
	LTK v LTK	674,726	831,868	39,930	395,969	323,426	759,325	91.3%
	LTK v PC	768,352	942,306	45,231	448,538	-	493,768	52.4%
	PC v LTK	1,145,935	1,392,638	58,491	667,074	535,218	1,260,782	90.5%
	PC v PC	1,585,790	1,912,933	80,343	916,295	-	996,638	52.1%
	Total	4,174,803	5,079,745	223,994	2,427,875	858,644	3,510,513	69.1%
Single Vehicle	Subject Vehicle:							
	LTK	264,944	320,786		160,393		160,393	50.0%
	PC	389,709	473,991		236,996		236,996	50.0%
	Total	654,653	794,777		397,389		397,389	50.0%
Vehicle to Other**	Subject Vehicle:							
	LTK	65,427	79,438		39,719		39,719	50.0%
	PC	135,208	162,973		81,487		81,487	50.0%
	Total	200,635	242,411		121,206		121,206	50.0%
Total BP applied				246,107	2,946,469	896,359	4,088,935	
				6.0%	72.1%	21.9%		
Total LPV meeting the ODD		5,030,091						
Total injured Non-Motorist and Motorcyclists			498,184					
Total injured LPV Occupants			6,116,933					
Total Injured Persons in crashes with LPV meeting the OD			6,615,117					
							Injured Person Reduction	
If non motorist collision with LPV replaced by Occupantless Vehicle							42,059	
If motorcylist(s) collision with LPV replaced by Occupantless Vehicle							17,769	
Subtotal: non-LPV occupants							59,828	
If Light Vehicle replaced with Occupantless Vehicle in crashes with another Light Vehicle							3,510,513	
If Light Vehicle replaced with Occupantless Vehicle in Single Vehicle Crashes							397,389	
If Light Vehicle replaced with Occupantless Vehicle in Non LPV crashes							121,206	
Subtotal: LPV occupants							4,029,107	
Final Estimate							4,088,935	

For reference, the distribution of injury severities for the injured LPV occupants described in Table 8 is provided in Table 9.

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[6] Note: The table indicates 5,030,091 LPVs, which differs slightly from the Table 2 estimate of 5,030,082 LPVs. This is a result of rounding during the application of weighting factors.

Table 9. Distribution of occupant injury severity in crashes occurring within the ODD.

Injury Severity	Frequency	Percent	Cumulative Frequency	Cumulative Percent
Possible Injury (C)	3,815,897	62.4%	3,815,897	62.4%
Suspect Minor Inj(B)	1,809,066	29.6%	5,624,963	92.0%
Suspect Serious Inj(A)	341,068	5.6%	5,966,031	97.5%
Inj, Sev Unk	150,902	2.5%	6,116,933	100.0%

Note: The numbers in the previous three tables may not match exactly due to rounding occurring within the weighted numbers.

SHRP 2 NDS Benefit Calculations

The unavailability of occupancy and occupant injury data, and the limited sample compared with the national databases, limited the ability to calculate potential OV benefits from the SHRP 2 NDS data. However, the calculated benefits are consistent with the findings from the national databases. Of the 1,681 SHRP 2 NDS events within the ODD, 1,167 were single-vehicle conflicts in which the subject vehicle struck an object or roadway feature. The remaining events were multi-vehicle conflicts composed of 899 personal vehicles, including automobiles, mini-vans, SUVs, and pickup trucks. Given the lack of crash-related fatalities in the SHRP NDS and the lack of detailed or estimated injury information, the calculation of benefits arising from the replacement of SHRP 2 NDS vehicles with an OV was mainly limited to changes in occupant exposure. An assessment across the crashes examined for this investigation indicated that a minimum of 1,308 occupants were present in the vehicles involved in the crashes of interest. If the OV is assumed to replace one of these vehicles in each crash, this translates to a calculated reduction in occupant exposure of at least 551 occupants (42% reduction). Note that an exact number of occupants is not known for the SHRP 2 NDS crashes due to the uncertainty of exact occupancy in non-subject vehicles (which were not instrumented). Additional benefit from the use of OVs would also be possible for crashes involving vulnerable road users. However, only four vulnerable road user collisions were identified within the ODD of interest in the SHRP 2 NDS data. No serious injuries were observed for any of these collisions. Therefore, no OV benefit based on vulnerable road user injury prevention or amelioration could be inferred from the SHRP 2 NDS data.

Discussion and Conclusions

One of the basic tenets of safety involves the separation of the individual from the source of harm. Whenever possible and practical, this is the preferred method for hazard mitigation. In traffic safety, this would translate to reducing the number of drivers, passengers, pedestrians, and other human actors on our roadways. New technologies such as OVs begin to offer some possibilities to replace some of the trips that humans take and consequently insulate them from the harm that automotive crashes represent. The goal of this effort was to establish an initial approach to assess the potential reduction in harm that OV technologies may offer and examine different ways in which these vehicles may contribute to a safer traffic environment.

The results of this investigation suggest that there is potential for these technologies to reduce the number of fatalities and injuries that occur on the nation's roadways. It is well established that automated driving systems could improve safety by avoiding the human errors that are a critical reason for most crashes, but this investigation shows there is also potential for OVs to significantly improve safety. Most of that reduction

will come from the removal of occupants who are simply making a trip to obtain goods that can be delivered by the OV. The extent of that reduction varies with respect to the consideration of injured persons or fatalities, with a larger proportion of injured persons than fatalities being avoided. Given the large number of pedestrians and other vulnerable roadway users that are fatally injured every year, this makes intuitive sense, as vehicle occupants are much better protected. However, the characteristics of OVs may also increase crash compatibility with vulnerable roadway users, given the less rigid structural elements required (as OVs do not need to protect vehicle occupants) compared to traditional vehicles.

The results of this investigation should not be taken as definitive benefit estimates. There are important assumptions inherent in the parameters that were used, and some of these assumptions may not be immediately realized. Rather, the results are meant to support critical thinking into how innovative technologies such as OVs may offer benefits that transcend the typical approaches used in vehicle safety, including passive and active safety measures. There is no expectation that 60% of fatalities or injured persons in the ODD of interest, or even half of these amounts, will immediately vanish. However, these figures provide a target to work towards and a benchmark to examine how fatality and injury numbers change as OVs become more prevalent and replace more "shopping and errand" trips.

Many assumptions were needed in the derivations of the benefit parameters. While the assumptions, and the parameters themselves, should receive thorough review and vetting, and may in some cases be proven unrealistic or inadequate, the framework that we have established for the calculation of benefits provides the flexibility to modify or replace these parameters as additional work in this area is completed. The approach taken to select the benefit parameters was purposefully conservative, in most cases reducing the potential benefits that were calculated compared to what existing data or the literature provided. We encourage the critical review of our work and assumptions, and the discussion that will result from these reviews. We believe open conversation can only help to improve the approaches proposed for estimating safety benefits derived from innovative technologies and thus provide realistic fatality and injury risk reduction targets.

Appendix A

Event Type Results for Effect of Vehicle Size

This section contains additional results tables to accompany Table 6 in the Results section of this document, which provides the overall results on the effect of vehicle size on crash outcome when the OV hypothetically replaces either the SV or POV. Tables are divided by event type category, which are a compilation of the Incident Type variable coded as part of the original SHRP 2 NDS data reduction effort (Hankey et al., 2016).

Crashes within SHRP 2 can be classified in terms of assigned severity (Table 10). More details about event severity can be found in Antin et al. (2019) and Hankey et al. (2016).

Table 10. Crash severity level definitions.

Severity Level	Category	Brief Description
I	Most Severe	Any crash that results in any injury requiring medical attention, or one that includes an airbag deployment or requires vehicle towing.
II	Police-reportable Crash	A crash that does not meet the requirements for a Level I crash, but does include sufficient property damage that warrants being reportable to the police.
III	Minor Crash	A crash that does not meet the requirements for a Level II crash but does result in minimal damage.
IV	Low Risk	Tire/curb strike

Table 11. Effect of vehicle size on crash outcome for SHRP 2 NDS <u>rear-end crashes</u> when either the SV or POV is hypothetically replaced by the model OV.

If SV = Model	Level I		Level II		Level III		All Levels	
	#	%	#	%	#	%	#	%
# Cases (assessed)	33		76		86		195	
# Cases avoided	0	0%	2	3%	15	17%	17	9%
# Cases uncertain	3	9%	11	14%	24	28%	38	19%
# Cases unchanged	30	91%	63	83%	47	55%	140	72%
If POV = Model	Level I		Level II		Level III		All Levels	
	#	%	#	%	#	%	#	%
# Cases (assessed)	33		75		86		194	
# Cases avoided	0	0%	2	3%	14	16%	16	8%
# Cases uncertain	3	9%	11	15%	25	29%	39	20%
# Cases unchanged	30	91%	62	83%	47	55%	139	72%
All Cases	Level I		Level II		Level III		All Levels	
	#	%	#	%	#	%	#	%
# Cases (assessed)	66		151		172		389	
# Cases avoided	0	0%	4	3%	29	17%	33	8%
# Cases uncertain	6	9%	22	15%	49	28%	77	20%
# Cases unchanged	60	91%	125	83%	94	55%	279	72%

Table 12. Effect of vehicle size on crash outcome for SHRP 2 NDS <u>sideswipe crashes</u> when either the SV or POV is hypothetically replaced by the model OV.

If SV = Model	Level I		Level II		Level III		All Levels	
	#	%	#	%	#	%	#	%
# Cases (assessed)	2		6		6		14	
# Cases avoided	0	0%	0	0%	0	0%	0	0%
# Cases uncertain	0	0%	2	33%	2	33%	4	29%
# Cases unchanged	2	100%	4	67%	4	67%	10	71%
If POV = Model	**Level I**		**Level II**		**Level III**		**All Levels**	
	#	%	#	%	#	%	#	%
# Cases (assessed)	2		6		6		14	
# Cases avoided	0	0%	1	17%	0	0%	1	7%
# Cases uncertain	1	50%	1	17%	2	33%	4	29%
# Cases unchanged	1	50%	4	67%	4	67%	9	64%
All Cases	**Level I**		**Level II**		**Level III**		**All Levels**	
	#	%	#	%	#	%	#	%
# Cases (assessed)	4		12		12		28	
# Cases avoided	0	0%	1	8%	0	0%	1	4%
# Cases uncertain	1	25%	3	25%	4	33%	8	29%
# Cases unchanged	3	75%	8	67%	8	67%	19	68%

Table 13. Effect of vehicle size on crash outcome for SHRP 2 NDS <u>intersection crashes</u> when either the SV or POV is hypothetically replaced by the model OV.

If SV = Model	Level I		Level II		Level III		All Levels	
	#	%	#	%	#	%	#	%
# Cases (assessed)	28		34		5		67	
# Cases avoided	1	4%	4	12%	0	0%	5	7%
# Cases uncertain	2	7%	9	26%	1	20%	12	18%
# Cases unchanged	25	89%	21	62%	4	80%	50	75%
If POV = Model	**Level I**		**Level II**		**Level III**		**All Levels**	
	#	%	#	%	#	%	#	%
# Cases (assessed)	28		33		4		65	
# Cases avoided	2	7%	4	12%	1	25%	7	11%
# Cases uncertain	1	4%	7	21%	0	0%	8	12%
# Cases unchanged	25	89%	22	67%	3	75%	50	77%
All Cases	**Level I**		**Level II**		**Level III**		**All Levels**	
	#	%	#	%	#	%	#	%
# Cases (assessed)	56		67		9		132	
# Cases avoided	3	5%	8	12%	1	11%	12	9%
# Cases uncertain	3	5%	16	24%	1	11%	20	15%
# Cases unchanged	50	89%	43	64%	7	78%	100	76%

Table 14. Effect of vehicle size on crash outcome for SHRP 2 NDS <u>opposite direction/head-on crashes</u> when either the SV or POV is hypothetically replaced by the model OV.

If SV = Model	Level I		Level II		Level III		All Levels	
	#	%	#	%	#	%	#	%
# Cases (assessed)	0		3		1		4	
# Cases avoided	0	NA	0	0%	0	0%	0	0%
# Cases uncertain	0	NA	3	100%	1	100%	4	100%
# Cases unchanged	0	NA	0	0%	0	0%	0	0%
If POV = Model	Level I		Level II		Level III		All Levels	
	#	%	#	%	#	%	#	%
# Cases (assessed)	0		3		1		4	
# Cases avoided	0	NA	0	0%	0	0%	0	0%
# Cases uncertain	0	NA	3	100%	1	100%	4	100%
# Cases unchanged	0	NA	0	0%	0	0%	0	0%
All Cases	Level I		Level II		Level III		All Levels	
	#	%	#	%	#	%	#	%
# Cases (assessed)	0		6		2		8	
# Cases avoided	0	NA	0	0%	0	0%	0	0%
# Cases uncertain	0	NA	6	100%	2	100%	8	100%
# Cases unchanged	0	NA	0	0%	0	0%	0	0%

Table 15. Effect of vehicle size on crash outcome for SHRP 2 NDS <u>backing crashes</u> when either the SV or POV is hypothetically replaced by the model OV.

If SV = Model	Level I		Level II		Level III		All Levels	
	#	%	#	%	#	%	#	%
# Cases (assessed)	3		7		70		80	
# Cases avoided	1	33%	0	0%	14	20%	15	19%
# Cases uncertain	0	0%	2	29%	23	33%	25	31%
# Cases unchanged	2	67%	5	71%	33	47%	40	50%
If POV = Model	Level I		Level II		Level III		All Levels	
	#	%	#	%	#	%	#	%
# Cases (assessed)	2		7		37		46	
# Cases avoided	1	50%	0	0%	6	16%	7	15%
# Cases uncertain	0	0%	1	14%	9	24%	10	22%
# Cases unchanged	1	50%	6	86%	22	59%	29	63%
All Cases	Level I		Level II		Level III		All Levels	
	#	%	#	%	#	%	#	%
# Cases (assessed)	5		14		107		126	
# Cases avoided	2	40%	0	0%	20	19%	22	17%
# Cases uncertain	0	0%	3	21%	32	30%	35	28%
# Cases unchanged	3	60%	11	79%	55	51%	69	55%

Table 16. Effect of vehicle size on crash outcome for SHRP 2 NDS <u>single driver crashes</u> when the SV is hypothetically replaced by the model OV.

If SV = Model	Level I		Level II		Level III		All Levels	
	#	%	#	%	#	%	#	%
# Cases (assessed)	16		15		110		141	
# Cases avoided	0	0%	0	0%	32	29%	32	23%
# Cases uncertain	2	13%	3	20%	21	19%	26	18%
# Cases unchanged	14	88%	12	80%	57	52%	83	59%
If POV = Model	**Level I**		**Level II**		**Level III**		**All Levels**	
	#	%	#	%	#	%	#	%
# Cases (assessed)	4		1		20		25	
# Cases avoided	0	0%	0	0%	11	55%	11	44%
# Cases uncertain	1	25%	1	100%	6	30%	8	32%
# Cases unchanged	3	75%	0	0%	3	15%	6	24%
All Cases	**Level I**		**Level II**		**Level III**		**All Levels**	
	#	%	#	%	#	%	#	%
# Cases (assessed)	20		16		130		166	
# Cases avoided	0	0%	0	0%	43	33%	43	26%
# Cases uncertain	3	15%	4	25%	27	21%	34	20%
# Cases unchanged	17	85%	12	75%	60	46%	89	54%

Table 17. Effect of vehicle size on crash outcome for SHRP 2 NDS <u>bicycle/pedestrian crashes</u> when the SV is hypothetically replaced by the model OV.

If SV = Model	Level I		Level II		Level III		All Levels	
	#	%	#	%	#	%	#	%
# Cases (assessed)	3		0		2		5	
# Cases avoided	0	0%	0	0%	0	0%	0	0%
# Cases uncertain	1	4%	0	0%	0	0%	1	20%
# Cases unchanged	2	7%	0	0%	2	40%	4	80%
If POV = Model	**Level I**		**Level II**		**Level III**		**All Levels**	
	#	%	#	%	#	%	#	%
# Cases (assessed)	0		0		0		0	
# Cases avoided	0	0%	0	0%	0	0%	0	NA
# Cases uncertain	0	0%	0	0%	0	0%	0	NA
# Cases unchanged	0	0%	0	0%	0	0%	0	NA
All Cases	**Level I**		**Level II**		**Level III**		**All Levels**	
	#	%	#	%	#	%	#	%
# Cases (assessed)	3		0		2		5	
# Cases avoided	0	0%	0	NA	0	0%	0	0%
# Cases uncertain	1	33%	0	NA	0	0%	1	20%
# Cases unchanged	2	67%	0	NA	2	100%	4	80%

Appendix B

Estimates of ODD-Specific Age-Adjusted Event Rates

As part of an effort to examine the susceptibility of self-driving vehicles to crashes, Blanco et al. (2016) used SHRP 2 NDS data to estimate comparative crash rates. Since the SHRP 2 NDS oversampled younger and older driver populations, calculation of a weighting factor was needed to make these crash rates more closely representative of national driving statistics. The required weights were calculated by dividing the percentages of U.S. licensed drivers grouped by age over the percentages of corresponding SHRP 2 NDS drivers in similar age bins (Table 18).

Table 18. Comparison of driver distributions by age group.

Age Group	Weight	Percentage in SHRP 2 NDS	Percentage of U.S. Licensed Drivers
16-24	0.32	37	12
25-39	1.53	17	26
40-54	2.33	12	28
55-74	1.35	20	27
75+	0.5	14	7

In this investigation, these weights were used to estimate the age-adjusted crashes and total mileage traveled by SHRP 2 NDS drivers within the ODD of interest. However, caution should be used when applying these weights to SHRP 2 NDS events in combination with the striking and struck vehicle designations. In multi-vehicle collisions within the ODD, the striking vehicle was the subject approximately 70% of the time, and therefore age information was not available for the driver in 30% of striking vehicles and 70% of struck vehicles.

Results

In order to estimate total SHRP 2 NDS mileage within the ODD, a vehicle speed restriction was implemented. Three variations of mileage were tallied and grouped by driver age. Included in these counts were totals of the SV driving at speeds less than or equal to 50 mph, 40 mph, and 30 mph (Table 19).

Table 19. Estimated total mileage in millions by age group and speed.

Age group	Mileage in millions when SV's speed <= 50 mph	Mileage in millions when SV's speed <= 40 mph	Mileage in millions when SV's speed <= 30 mph
Null	0.15	0.09	0.03
16-24	4.51	2.58	0.94
25-39	2.14	1.22	0.44
40-54	1.71	1.00	0.35
55-74	2.32	1.38	0.50
75+	1.46	0.95	0.37

Utilizing the weights as defined in Blanco et al. (2016), age corrections were applied to these estimates. Note that ~2% of SHRP 2 NDS drivers did not have age information available and were omitted from the age-adjusted calculation (Table 20).

Table 20. Estimated total mileage in millions by age group and speed, age adjusted.

Age group	Weight	Mileage in millions when SV's speed <= 50 mph	Mileage in millions when SV's speed <= 40 mph	Mileage in millions when SV's speed <= 30 mph
16-24	0.32	1.44	0.83	0.30
25-39	1.53	3.28	1.87	0.68
40-54	2.53	4.32	2.52	0.90
55-74	1.35	3.14	1.86	0.67
75+	0.50	0.73	0.47	0.19

A further breakdown of crashes was desired in terms of their assigned severity, which is defined in Appendix A, Table 10. SHRP 2 NDS crashes within the ODD were queried for counts of struck vehicle type by event severity (Table 21). Age information was only known for the subject driver. Because of this, the tables below only include crashes where the subject was in the struck vehicle. Within the ODD, the SV was struck in approximately 30% of all non-single-vehicle crashes. All crashes in Table 21 and those that follow occurred in a speed limit zone of 45 mph or below.

Table 21. Number of collisions by struck vehicle type where subject driver is struck. Crashes are restricted to those occurring within a maximum 45-mph speed limit zone.

	I - Most Severe				II - Police-reportable Crash				III - Minor Crash			
Age group	Automobile	Pickup truck	SUV	Van	Automobile	Pickup truck	SUV	Van	Automobile	Pickup truck	SUV	Van
16-24	10	0	1	0	20	2	8	1	31	1	6	0
25-39	5	0	2	0	8	0	3	0	3	0	2	0
40-54	2	0	1	1	6	0	3	0	4	0	1	1
55-74	2	0	0	0	8	0	2	0	3	1	1	0
75+	2	0	0	1	5	0	0	1	7	0	1	0

Using the same weights from the mileage estimate, age adjustments were applied to the struck vehicle counts (Table 22). It should be noted that weighting did not consider the prevalence of crash type by age group (e.g., whether teen drivers are more likely than older drivers to be involved in rear-end strike crashes).

Table 22. Number of collisions by struck vehicle type where subject driver is struck, age adjusted.

		I - Most Severe				II - Police-reportable Crash				III - Minor Crash			
Weight	Age Group	Autom obile	Pickup truck	SUV	Van	Autom obile	Pickup truck	SUV	Van	Autom obile	Pickup truck	SUV	Van
0.32	16-24	3.2	0	0.32	0	6.4	0.64	2.56	0.32	9.92	0.32	1.92	0
1.53	25-39	7.65	0	3.06	0	12.24	0	4.59	0	4.59	0	3.06	0
2.53	40-54	5.06	0	2.53	2.53	15.18	0	7.59	0	10.12	0	2.53	2.53
1.35	55-74	2.7	0	0	0	10.8	0	2.7	0	4.05	1.35	1.35	0
0.5	75+	1	0	0	0.5	2.5	0	0	0.5	3.5	0	0.5	0

Finally, an estimate of crash rate per million miles was calculated by dividing the age-adjusted crash counts by the age-adjusted mileage (Table 23). These rate estimates use only those crashes where the subject driver was struck and occurred within a maximum 45 mph speed limit zone. Mileage was counted only when the vehicle travel speed was 50 mph or less.

Table 23. Age-adjusted SHRP 2 crash rates per million miles driven.

	I - Most Severe				II - Police-reportable Crash				III - Minor Crash			
Age Group	Autom obile	Pickup truck	SUV	Van	Autom obile	Pickup truck	SUV	Van	Autom obile	Pickup truck	SUV	Van
16-24	2.22	0.00	0.22	0.00	4.43	0.44	1.77	0.22	6.87	0.22	1.33	0.00
25-39	2.33	0.00	0.93	0.00	3.73	0.00	1.40	0.00	1.40	0.00	0.93	0.00
40-54	1.17	0.00	0.59	0.59	3.51	0.00	1.76	0.00	2.34	0.00	0.59	0.59
55-74	0.86	0.00	0.00	0.00	3.44	0.00	0.86	0.00	1.29	0.43	0.43	0.00
75+	1.37	0.00	0.00	0.68	3.42	0.00	0.00	0.68	4.78	0.00	0.68	0.00

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