

Potential Safety Effects of Low-Mass Vehicles with Comprehensive Crash Avoidance Technology

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Abstract A statistical simulation was performed to explore the effect on injuries and crash distribution if some vehicles were replaced with low-mass vehicles (LMVs) that could not cause a crash due to comprehensive crash avoidance systems. Analysis was based on crash distributions in the 2002-2009 NASS-GES and NASS-CDS datasets. The predicted distributions of injury and crashes are based on the current distribution of crashes, a shift in delta V caused by mass reduction, risks of injury for each crash mode, and a differing distribution of crash types resulting from comprehensive crash avoidance systems. If a vehicle could not cause a crash, it would be involved in 63% fewer crashes on average, including 93% fewer frontal impacts and 85% fewer rollovers; side and rear impacts would comprise a greater proportion of the remaining crash population. Risk of injury in frontal impact would be lower because of the substantially reduced exposure. However, risk of injury in near-side impacts would be higher because of a higher delta V resulting from the lower mass. This study demonstrates techniques for estimating the change in fleet delta V distribution given the introduction of low-mass vehicles. It also identifies how the phase-in of crash avoidance technologies might affect crashworthiness priorities.

Keywords crash avoidance technologies, injury risk, low-mass vehicles, safety priorities

I. INTRODUCTION

Priorities in vehicle occupant crash protection are driven by the distribution of crash types and the severity of the resulting injuries. In the U.S., frontal impacts have historically been the most severe (measured by the median delta V, or change in velocity that occurs during a crash) and caused the most injuries [1, 2, 3]. Hence, occupant restraints and crashworthiness regulations first targeted this crash mode, with considerable success in reducing injuries and fatalities in recent decades [4, 5]. Progress in protecting occupants in frontal impacts led to increasing the relative importance of side impact, which has gained increased attention in recent years [6, 7]. The ongoing introduction of crash avoidance technology will change priorities again, because these technologies affect crash types unequally [8, 9]. For example, electronic stability control (ESC) has produced large reductions in high-severity single-vehicle crashes, particularly rollovers [10, 11], but has minimal effect on two-vehicle lane-change/merge crashes.

Concurrently, the rapid increases in fuel economy mandated by current and proposed Federal rules are likely to shift the fleet toward smaller, lower-mass vehicles [12, 13]. Reduced mass affects crash injury risk differentially across crash types, with the greatest increase occurring in multiple-vehicle planar crashes. Green et al. [14] performed a comprehensive review of research estimating the effects of reducing vehicle mass on fatality risk. They found inconsistent results from different authors, with some predicting increases in fatalities with average fleet mass reduction and others predicting no change.

These trends interact because the benefits of adding a particular type of crash avoidance technology to a vehicle depends on the mass of the vehicle as well as other characteristics affecting crash type and crash severity distributions [8, 15]. Consequently, the priorities for crashworthiness and occupant protection can be expected to change with increasingly effective crash avoidance and reduced mass for some vehicles. The effectiveness of different crash avoidance technologies varies, and most technologies only apply to a subset of crash types [8]. The current study uses statistical simulation to explore the effect on injuries and crash distribution for the best-case scenario of a vehicle that would never cause a crash. As an example, single-vehicle run-off-road crashes would no longer occur. The simulation also considers the effect of introducing low-mass vehicles (LMV), which will change the distribution of crash severity because of their lower mass.

II. METHODS

The injury frequency from motor-vehicle crashes depends on four key factors. The first is exposure, which in this case is the number of crashes that occur per year. The second factor is crash type, because occupants are injured differently in frontal, side, and rear impacts. The third factor is crash severity, which is the key predictor of injury severity. The fourth factor is the type of occupant protection, which includes safety features such as seatbelts and airbags. The subsequent sections describe how each of these components was estimated for a vehicle with comprehensive crash avoidance technology (CCAT) while accounting for a vehicle mass reduced to either 500 or 800 kg.

Crash Environment Models

Data analysis was conducted using the National Automotive Sampling System: General Estimates System (NASS-GES) dataset for crash years 2002-2009. The GES dataset is a national sample of police-reported motor-vehicle crashes that include property damage, injury, or death. The dataset gains approximately 50,000 crashes from 60 areas across the United States each year. Using these data for the current analysis assumes the current level of crash avoidance technology in vehicles other than the LMV.

To perform the exercise of identifying the crash and injury environment for a low-mass vehicle with CCAT, we define the following conditions for such a vehicle:

- The vehicle would never be the striking vehicle in a crash.
- Single-vehicle crashes involving loss of control will not occur, except for those involving icy/snowy roads.
- Single-vehicle crashes into pedestrians will not occur, except for those classified as “pedestrian darting/dashing into roadway.”
- Animal-related collisions will not occur.
- Mass range of 500-800 kg.
- Track width of 1.5 m.
- Wheelbase of 2.0 m.
- Stiffness comparable to subcompact cars currently on the market.
- Drivers who would choose a LMV are assumed to be typical urban drivers in terms of gender, age, and current vehicle type.
- Seatbelt interlock features mean all occupants would be belt-restrained.
- Airbags have presence and effectiveness equivalent to that found in the fleet being analyzed.
- Maximum speed of the LMV would be 120 km/hr.

Injury Risk Models

Injury risk assessments were based on the National Automotive Sampling System: Crashworthiness Data System (NASS-CDS) a national sample of towaway crashes in the United States involving light vehicles, using case years from 2002-2009. This dataset includes in-depth accident investigations and occupant medical information for 5,000 crashes per year. These years were selected for analysis because they have limited penetration of crash avoidance technologies. Logistic regression analysis was used to estimate risk of any AIS2+ or AIS3+ injury separately for frontal, near-side, far-side, and rear crashes. Cases involving multiple impacts were classified according to the first impact. Injury risk curves were developed as a function of crash severity, belt restraint, age, and gender so they can be generated to represent a belted population. For the current study, occupants are considered belted at all times. Injury analyses were based on only adult occupants, and results are presented for a belt-restrained, 40-year-old male occupant.

For rollover injury estimates, the annual number of occupants injured in rollovers was averaged over NASS-CDS years 2002-2007. Overall risk of AIS2+ and AIS3+ injury based on occupant restraint was calculated, since crash severity measured in terms of change of velocity (delta V) does not apply to rollover crashes.

Estimating changes in delta V

The introduction of LMV into the vehicle fleet will change the distribution of crash severity, defined in this analysis as the change of velocity experienced by the vehicle in a crash (delta V)

The average mass of recent subcompact vehicles is 1155 kg. The LMV under consideration has a mass of 500-800 kg. In a crash involving the LMV, the delta V of the LMV will increase while the delta V of the other vehicle will decrease. The program WinSmash is used to estimate crash severity in NASS crash investigations using

measured damage from the crashed vehicle [16, 17]. The program uses stiffness values based on NHTSA's regulatory and consumer information testing programs.

An exercise was performed using WinSmash to simulate a variety of crashes where a subcompact vehicle was replaced with a LMV. The goal was to estimate how delta V would change for the two vehicles using the same crush damage and stiffness of a subcompact car, but having the dimensions and mass of the LMV. Fifty crashes from NASS-CDS case years 2006-2009 involving a subcompact vehicle were identified where there were crush measurements available for both the subcompact and other vehicle. The vehicle and damage characteristics from the case file were input into WinSmash. The dimensions of the LMV (needed to calculate delta V in Winsmash) replaced those of the subcompact car, and the mass was adjusted to be either 800 or 500 kg.

Calculating Exposure

For occupants in a LMV with CCAT, overall crash exposure will be reduced because many crashes will be eliminated by the technology. The distribution of crash types and associated injuries will also change because crash avoidance technology reduces some types of crashes more than others. The severity of crashes experienced by occupants of a LMV will likely increase because of the reduced mass of the vehicle.

The current risk of being in a frontal, near-side, far-side, or rear impact as a function of crash severity was generated using the weighted probability of different crash types in the NASS-GES dataset. Because this dataset does not include a measure of crash severity, the distribution of crashes by severity was estimated using a technique described by Flannagan [18]. For a given set of crashes in NASS-GES, the overall distribution of crash severity can be estimated by calculating the distribution of injuries using the police-reported KABCO scale, and applying a relationship derived from NASS-CDS between delta V and KABCO.

The predicted exposure for a vehicle with CCAT was estimated by removing all of the crashes in the current distribution that would not occur if CCAT were available. This process considers the different types of pre-crash scenarios that make up differing proportions of frontal, side, rear, and rollover impacts [15]. The elimination of these crashes was assumed to be uniform across the range of delta V and randomly over the set of rollover crashes. The crash risk vs. delta V curve for planar crashes is then shifted upwards to account for the changes in delta V that would result with LMV of 800 or 500 kg.

Estimating Injury Counts

The exposure curves for different crash environments were then multiplied by the relevant injury risk curves and multiplied by the total number of current crashes (for each mode) to estimate the annual number of injuries that would occur in each environment. To summarize how the injury patterns would change for each crash mode in each crash environment, the areas under the injury frequency curves were calculated to estimate the total number of injuries. The values were then divided by the current number of total injuries to estimate a relative risk compared to the current environment.

For rollover crashes, the average annual number of injured occupants was reduced by the percentage of crashes that would not occur. The remaining counts were adjusted to account for all occupants being belted using risk ratios between belted and unbelted occupants. For rollovers, no adjustments to injury count based on mass were made.

III. RESULTS

Error! Reference source not found. shows the distributions of crash types as a percentage of the current number of crashes for the current crash environment and for a CCAT vehicle. The most dramatic change is the reduction of frontal impacts from 47% of all crashes to 3%. Rollovers make up 2.5% of all current crashes, which would fall to 0.4% for a vehicle in a CCAT environment. **Error! Reference source not found.** shows the percentage of each type of crash that would be prevented with CCAT. Overall, 63% of crashes would be prevented. The most drastic change is the 93% reduction in frontal crashes. Rollovers would also see a substantial drop, with 85% of crashes prevented. Reductions in rear and side impacts range from 29 to 39%. The change in crash distribution brings substantial changes in the relative importance of different crash modes. The distribution of crashes in current and CCAT vehicles are shown in **Error! Reference source not found.**. Frontal crashes fall from 47% to 9% of the crash population, while the proportion of rear impacts almost doubles from 22% to 43%. Side impacts also increase substantially from 29% to 47% of crashes.

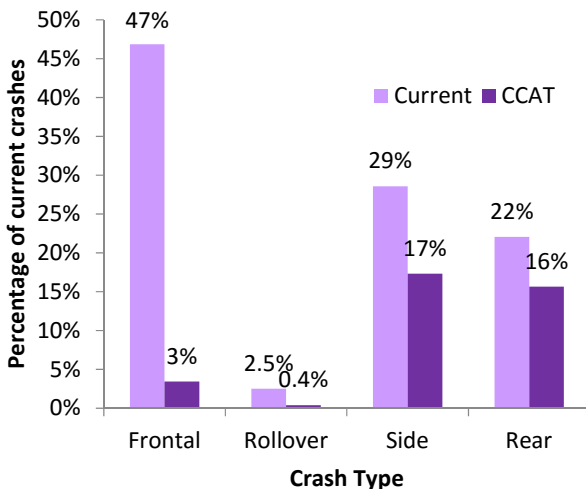


Fig 1. Distribution of crash types for current and CCAT environments.

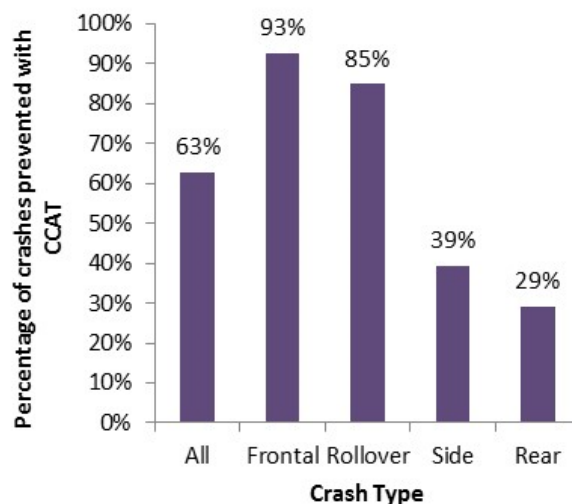


Fig 2. Percentage of crashes avoided with CCAT.

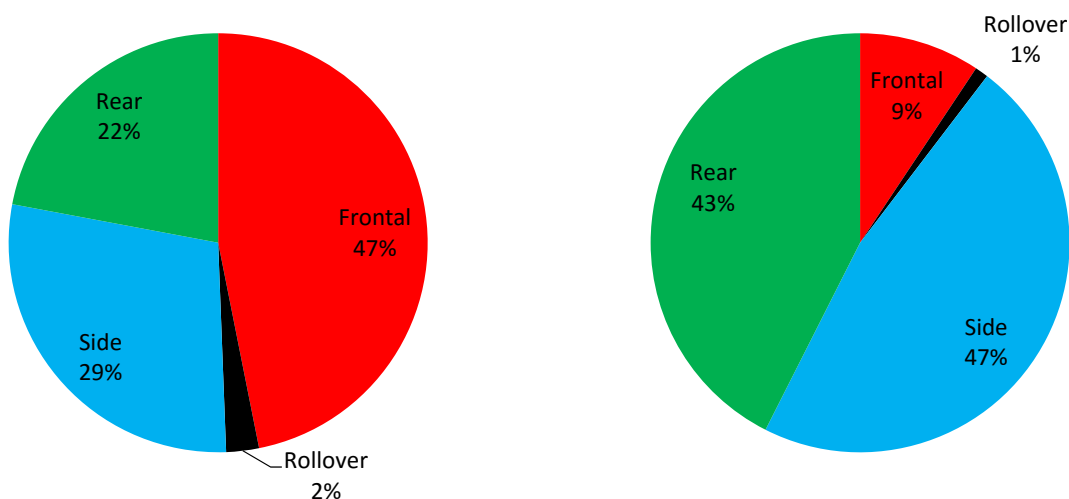


Fig. 3. Comparison of crash type distribution in current environment (left) and CCAT environment (right).

Injury and fatality risk curves for frontal, near-side, far-side, and rear impacts are shown in Figure 4. The risk curves for overall AIS2+ and AIS3+ injury include all body regions. When occupant characteristics are predictors, results are presented for belted 40-year-old males. Injury risk is highest in near-side impacts, similar in frontal and far-side impacts, and lowest in rear impacts. Delta V is a predictor for all injuries that were considered, and age was a significant predictor for everything but AIS2+ injuries in rear impacts. Belt use was a predictor for injury in each crash mode. Women had a higher risk of AIS2+ and AIS3+ injuries in frontal crashes and AIS3+ injuries in near-side crashes, while men had a higher risk of AIS2+ injury in rear impacts. Although these risk curves are generated from current data, they are assumed to apply to occupants of LMV with CCAT.

The data from the WinSmash delta V distributions is shown in Figure 5 for the LMV and Figure 6 for the other vehicle. On average, the total delta V for the LMV increased by 42% or 80%, respectively, with the 800 and 500 kg mass substitutions. The delta V of the other vehicle decreased by 18% on average. There is a weak relationship with the mass of the other vehicle in the crash.

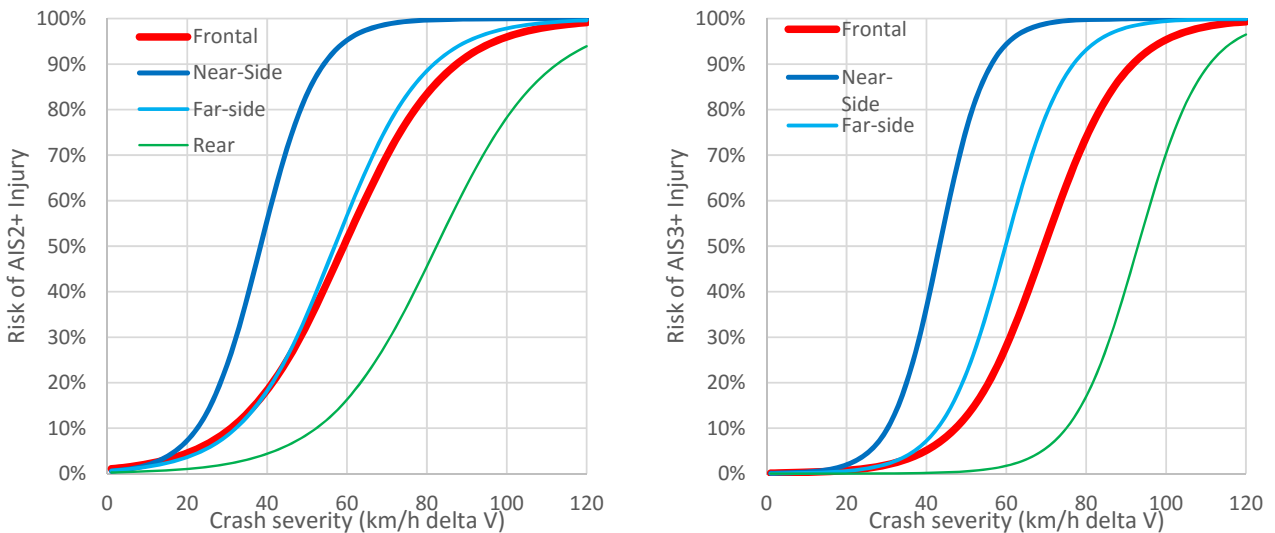


Fig. 4. Risk of injury vs. crash severity for each crash type. AIS2+ (left) and AIS3+ (right)

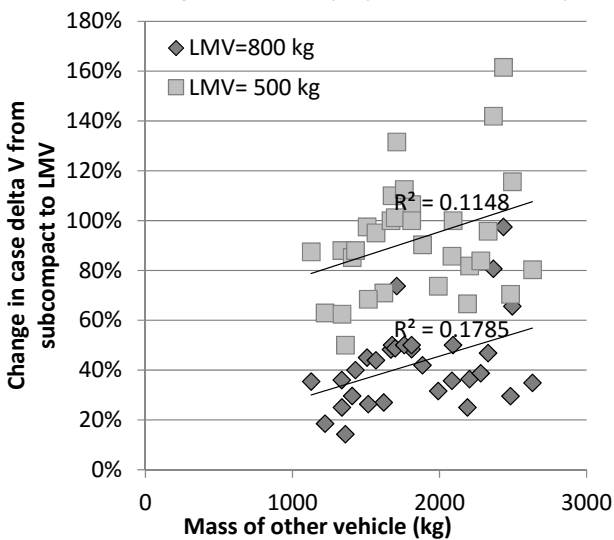


Fig. 5. Estimated change in delta V in case vehicle when changing from a subcompact to a LMV vs. the mass of the other vehicle.

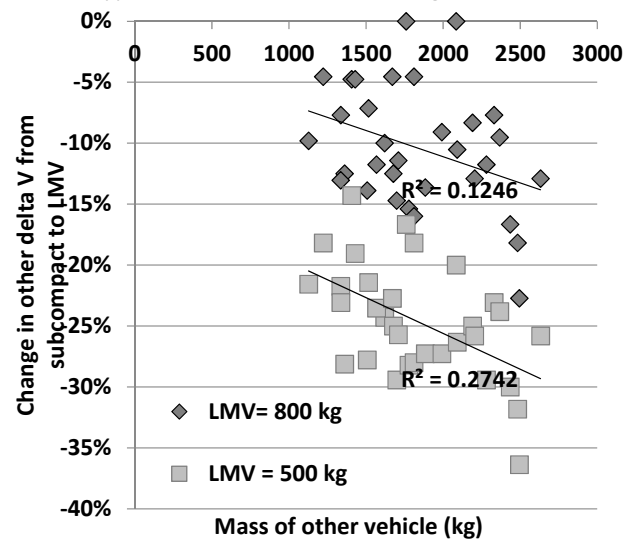


Fig. 6. Estimated change in delta V for the other vehicle when changing from a subcompact to a LMV vs. the mass of the other vehicle.

Appendix A contains plots, as a function of delta V, of the risk of a crash and the annual number of AIS2+ and AIS3+ injured occupants for frontal, rear, near-side, and far-side impacts. Each plot contains data describing the current crash environment, a CCAT environment, an 800-kg LMV with CCAT, and a 500-kg LMV with a CCAT. Figure 7 and Figure 8 show the relative risk of AIS2+ and AIS3+ injury from each crash mode for each of the four crash environments based on the information presented in the Appendix, as well as a count of injured occupants in rollovers based on NASS-CDS. For AIS2+ injuries, overall risk would drop with CCAT to 31% of the current risk, largely due to reductions in frontal impact injuries. An LMV of 800 kg with CCAT would still have overall lower risk of 61% compared to the current environment, with a greater number of injuries from side and rear impacts. An LMV of 500 kg with CCAT would have slightly higher overall risk with a very different distribution of injury by crash mode. Patterns are similar with AIS 3+ injuries, except that the 800 kg LMV environment would have a similar overall rate of injury to the current environment, while the 500 kg LMV would result in approximately twice the risk of injury.

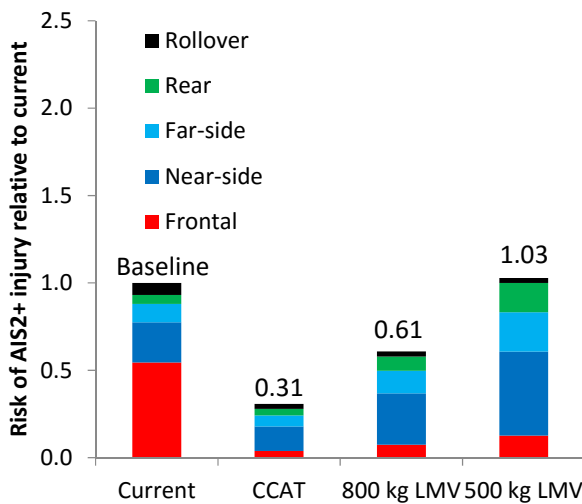


Fig. 7. Relative risk of AIS2+ injury for CCAT and LMV vehicles compared to current.

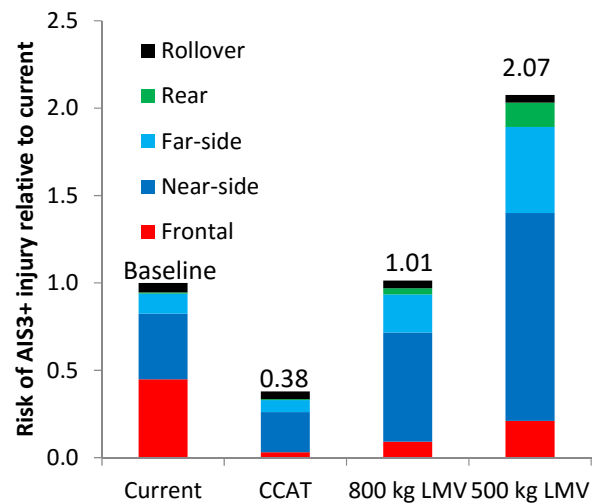


Fig. 8. Relative risk of AIS3+ injury for CCAT and LMV vehicles compared to current.

IV. DISCUSSION

This study demonstrated that significant shifts in the distribution of crash types would be expected for vehicles equipped with CCAT, where the vehicle could never cause a crash. The most dramatic changes would be 93% fewer frontal impacts and 85% fewer rollovers. If the vehicles with CCAT were designed to have lower masses of 800 or 500 kg, the advantages gained from reduced exposure to crashes would be somewhat offset by the increased crash severity resulting from the decrease in mass. For frontal impacts, the reduced exposure is substantial enough that the estimated risk of injury in frontal impacts with LMVs would still be lower than the current crash environment. However, for other crash modes, the increase in delta V may outweigh the benefits of reduced exposure. In near-side crashes, the annual risk of injury for occupants of LMV would be 1.5 to 3.2 times higher than the current near-side crash environment. The risk of far-side injuries would increase by a factor of 1.2 to 4.3. Injuries from rear impacts would increase 1.6 to 17.8 times because of a shift into a higher delta V range. Currently, rear impacts most often occur at a lower range of crash severities. The number of occupants injured in rollovers would be reduced by 60%.

In this analysis, delta V was estimated to increase by 40-82% if the mass of the LMV was 800 or 500 kg compared to the current average subcompact mass near 1150 kg. The crash severity of the other vehicles involved in a crash with the LMV was estimated to go down by an average of 18%. These estimates are based on simulations with WinSmash that assume that the stiffness and damage to the LMV would be the same as that found in current subcompact vehicles, which may or may not be a reasonable assumption. In addition, the severity of remaining crashes may also be affected by crash avoidance technology, which was not addressed in the current study. For example, we assumed that ESC would not prevent crashes that occur on icy roads. For the remaining crashes involving LMV, it is possible that crash avoidance technologies might mitigate the severity of the crash even if they do not prevent the crash; this possible effect was not considered in the current analysis because the focus was on a scenario where the vehicle with CCAT would not be able to cause a crash. This would further reduce the number of injuries that occur.

Another limitation is the assumption that the injury risk curves developed using the current vehicle fleet can be applied to the LMV. Though only crashes occurring between 2002 and 2009 were considered, the levels of occupant protection in this vehicle fleet vary considerably. Moreover, it may be difficult to maintain the same levels of occupant protection when reducing vehicle mass by 300 to 500 kg from typical subcompact vehicle weights. Analysis of rollover injury was limited to 2002 to 2007 years because of a large dropoff in injury counts for 2008 and 2009, possibly caused by economic factors or initial penetration of ESC into the vehicle fleet.

Another assumption is that the severities of the crashes that are not prevented are the same severities as those that remain. To look at this, we compared the maximum injury in each vehicle for the original crash population and the non-prevented crash population. In both populations, 83% of crashes resulted in no injury. In the three most severe categories (Killed (K), Incapacitating (A), Non-incapacitating (B)), injury rates were lower in the remaining crashes compared to the original crash distribution (K: 56% reduction; A: 30% reduction;

B: 23% reduction). The only severity level that went up in the remaining crashes was Possible Injury, which is the least severe of the injury categories, rising by 20%.

The current analysis was not able to examine how pedestrian and cyclist impacts might change with introduction of a LMV. In the dataset used to identify which crashes would be prevented with CCAT, almost all pedestrian and cyclist crashes are coded as being caused by the striking vehicle. Thus almost no pedestrian and cyclist crashes would occur with CCAT vehicles. In addition, because this study focused on identifying occupant protection priorities for the occupant of the LMV, the outcome of pedestrians and cyclists struck by LMVs would not be expected to affect the LMV occupant's outcome.

The simulations performed in this study assumed a best-case scenario that a CCAT would not be able to cause any crashes. In reality, different crash avoidance technologies are estimated to prevent 5 to 65% of particular types of crashes, and future research should examine the range of remaining crashes while considering more realistic estimates of effectiveness. In addition, some CCAT may help prevent the case vehicle from being the struck vehicle in a crash, which was not considered in the current analysis. However, by simulating an environment with 100% effectiveness at preventing particular types of crashes, we can identify that the highest priority for occupant protection in CCAT vehicles should be improving protection to occupants in near-side impacts. However, the injury risks for near-side impacts used in the simulation are likely a worst-case estimate, because the dataset used to generate the injury risk curves has a limited number of vehicles equipped with side impact airbags. Far-side crashes would be the next crash mode to prioritize with regard to occupant protection.

Injuries from frontal impacts would happen much less frequently than the current crash environment because of the substantially reduced exposure. Allowable injury risk in frontal impacts could increase and still have fewer injuries than the current frontal crash environment. However, another perspective is that if the current level of frontal crash protection could be maintained in an LMV, the reduced number of injuries in frontal impact would help offset the increase in injuries from side impact.

Although rear impacts would make up a greater proportion of the crash population than they do now, they do not make up a significant part of the AIS2+ injury problem. However, the most common injuries in rear impacts are usually considered AIS1 severity. Analysis at this injury level was not performed because the lowest severity injury data are not considered reliable in NASS-CDS [19]. While higher-level injuries from rear impact would not be a key consideration in LMV, there may still be frequent AIS1 level injuries.

V. CONCLUSIONS

The simulations performed in this study demonstrate a technique for estimating occupant protection priorities as crash avoidance technologies are introduced into vehicles and vehicle mass is reduced. By examining the best-case crash avoidance scenario in which a vehicle could never cause a crash, the analysis highlights the possible changes in occupant protection priorities as the effectiveness of crash avoidance technologies increases over time. Side impacts will become the highest priority, followed by rear impacts, as the risk of injury from frontal and rollover crashes decreases. The study also developed a technique for estimating how crash severity distributions would change with the introduction of more low-mass vehicles into the fleet.

VI. ACKNOWLEDGEMENT

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VII. REFERENCES

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VIII. APPENDIX

