Impact of Improving Vehicle Front Design on the Burden of Pedestrian Injuries in Germany, USA, and India

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ABSTRACT

Objective: European car design regulations and New Car Assessment Program (NCAP) ratings have led to reductions in pedestrian injuries. The aim of this study was to evaluate the impact of improving vehicle front design on mortality and morbidity due to pedestrian injuries in a European country (Germany) and two countries, (USA, and India) that do not have pedestrian-focused NCAP testing or design regulations.

Methods: We used data from the International Road Traffic and Accident Database and the Global Burden of Disease project to estimate baseline pedestrian deaths and non-fatal injuries in each country in 2013. The effect of improved passenger car star ratings on probability of pedestrian injury was based on recent evaluations of pedestrian crash data from Germany. The effect of improved heavy motor vehicle (HMV) front-end design on pedestrian injuries was based on estimates reported by simulation studies. We used burden of disease methods to estimate population health loss by combining the burden of morbidity and mortality in Disability-Adjusted Life Years (DALYs) lost.

Results: Extrapolating from evaluations in Germany suggest that improving front end design of cars can potentially reduce the burden of pedestrian injuries due to cars by up to 24% in the US and 41% in India. In Germany, where cars comply with the UN regulation on pedestrian safety, additional improvements would have led to a 1% reduction. Similarly, improved HMV design would reduce DALYs lost by pedestrian victims hit by HMVs by 20% in each country. Overall, improved vehicle design would reduce DALYs lost to road traffic injuries (RTIs) by 0.8% in Germany, 4.1% in USA, and 6.7% in India.

Conclusions: Recent evaluations show strong correlation between Euro NCAP pedestrian scores and real-life pedestrian injuries, suggesting that improved car front design in Europe has led to substantial reductions in pedestrian injuries. Although the US has fewer pedestrian crashes, it would nevertheless benefit substantially by adopting similar regulations and instituting pedestrian NCAP testing. The maximum benefit would be realized in low- and middle- income countries like India that have a high proportion of pedestrian crashes. While crash-avoidance technologies are being developed to protect pedestrians, supplemental protection through design regulations may significantly improve injury countermeasures for vulnerable road users.

KEYWORDS

pedestrian; accidents, traffic; motor vehicles; vehicle design; vehicle safety

INTRODUCTION

Globally, 1.4 million people are killed and 97 million are injured in road traffic crashes every year (Haagsma et al., 2016). The overall disease burden, along with the mortality rate, from road traffic crashes is particularly high in Low- and Middle- Income Countries (LMICs). The disease burden refers to the impact of a problem on population heath and is quantified using a summary measure of population health like Disability-Adjusted Life Years (DALYs) lost (Mathers et al., 2001). The DALY is a measure that is used to quantify years lost due to poor health and takes into account both morbidity and mortality. In 2013, 89% of the DALYs lost from road traffic crashes occurred in LMICs. Pedestrians are disproportionately impacted in LMICs, accounting for 38% of all DALYs lost from road traffic crashes, compared to 20% in High-Income Countries (HICs) (IHME, 2016).

Numerous studies have shown that vehicles can be made to be safer so that pedestrians are not injured as severely when they are struck (Carter et al., 2005; Chawla et al., 2000; Feist et al., 2008; Lakshminarayana et al., 2011; Pastor, 2013; Ramli & Yamazaki, 2012; Strandroth et al., 2014). Regulations exist (UN 127) regarding the design of passenger cars for pedestrian safety performance (United Nations, 2015a). Further, the Euro New Car Assessment Program (NCAP) performs pedestrian crash testing and assigns cars a star rating based upon how well they perform. Evidence from Germany suggests that improvements in car design due to regulations and competition resulting from NCAP testing have been effective in reducing pedestrian injuries in real-world crashes (Pastor, 2013; Strandroth et al., 2014). However, most countries are not contracting parties to the UN 127 regulations for pedestrian safety and do not have NCAP programs that test for pedestrian protection (Ariffin et al., 2013). Notably, this includes the United States and most LMICs, such as India.

The aim of this study was to assess the impact of improved pedestrian-related vehicle safety standards on the burden of injury in three countries representing three separate scenarios: one country where new cars sold are required to meet pedestrian safety regulations and are tested by an NCAP program (Germany), one high income country (USA) and one lower-middle-income country (India) that do not have car design regulations nor conduct NCAP testing related to pedestrians.

METHODS

We reviewed secondary sources for estimating the baseline incidence of injuries and the effect of improved vehicle design on reducing pedestrian injuries and deaths. Figure A1 (see appendix) outlines the steps we used to achieve this. The main assumptions that were made in this study are outlined in Table A1.

Estimating the Burden in 2013

The 2013 revision of the Global Burden of Disease (GBD-2013) database was used to determine the number of pedestrian fatalities for India disaggregated by sex and seventeen 5-year age groups (IHME, 2016). GBD is a systematic effort to quantify the comparative magnitude of health loss due to all diseases and injuries, including road traffic injuries, in all countries since 1990. The project aimed to access and assess all empirical measurements of

population health that could inform estimates of the incidence of fatal and non-fatal road injuries. Date was included data from vital registration systems, verbal autopsy studies, mortuary/burial registers, household surveys, hospital databases, and prospective studies of disability outcomes following injuries. Among these, the most important data sources for traffic deaths were national death registration data in the US and Germany and a national verbal autopsy survey in India. The burden of non-fatal road injuries was estimated by first calculating the incidence of non-fatal crashes using population-based data (e.g., household surveys), then estimating the complications from crashes using hospital data. The duration of disability was estimated based on prospective follow-up studies, and finally, health loss was estimated by applying disability weights (a number on a scale from 0 to 1 that represents the severity of health loss associated with a health state).

GBD overestimates road traffic deaths in OECD countries (Bhalla & Harrison, 2015b). Therefore, the total number of pedestrian deaths for Germany and USA were obtained from the International Road Traffic and Accident Database (IRTAD), which provides official statistics from these countries (IRTAD, 2015). The total pedestrian deaths for Germany and USA were then disaggregated by age and sex using the proportions from GBD-2013.

Official statistics under-report the incidence of non-fatal injuries in most countries (Amoros & Noble, 2011). Therefore, the incidence of non-fatal injuries in these countries was estimated based on the total national non-fatal road injury cases reported by GBD (Bhalla et al., 2014), combined with the age- and sex- specific case fatality rates estimated by Corso et al. for the USA (Corso et al., 2006).

The most recent vital registration data available from Germany (2012) and the USA (2010) were used to construct a who-hit-whom matrix to determine the proportion of pedestrians that are fatally injured by passenger cars and by HMVs (World Health Organization, 2015), whereas for India, the proportion was estimated using data from a province in India (Bhalla, 2015). The effect of vehicle speed, which likely varies substantially in each of these countries, was not included in our analysis because it has been shown that improved design for pedestrian safety is relevant at both low and high speeds (Strandroth et al., 2014).

Burden Calculator, a software tool for estimating burden of injuries (DALYs) from count data, was used to calculate the number of DALYs lost in each country, stratified by age, sex, and vehicle type (Bhalla & Harrison, 2015a). Population data for each country in 2013 was retrieved from the United Nations World Population Prospects database (United Nations, 2015b). All parameters that are required to calculate DALYs from fatal and non-fatal injury incidence data are based on GBD-2010 and GBD-2013 and are included in Burden Calculator. DALYs are calculated using the following equation:

$$\text{DALYs} = \text{YLLs} + \text{YLDs} \qquad (1)$$

where YLLs = Years of Life Lost and YLDs = Years Lost to Disability.

YLLs were calculated by subtracting the person's age when they died from their life expectancy at the age of their death. YLDs were calculated using the following formula:

$$YLDs = N \cdot p_{perm} \cdot DW_{perm} \cdot L_p + N \cdot (1-p_{perm}) \cdot DW_{st} \cdot D_{st} \quad (2)$$

where N is the number of incident cases of each sequela, p_{perm} is the proportion of cases that will have permanent disability, DW_{st} is short-term & DW_{perm} is permanent disability weight, L_p is life expectancy, and D_{st} is the duration of short-term conditions.

The DALYs lost by road user type for each of the three countries was calculated, as was the DALYs lost by pedestrians according to the impacting vehicle type.

Estimating the Impact of Improved Vehicle Design on the Burden in 2013

Passenger Cars: For passenger cars, we aimed to estimate the reduction in pedestrian injury burden in each country that would result if all passenger cars scored at least 3 stars in Euro NCAP pedestrian protection testing. In Germany, no cars received a 3-star rating in 1997, but by 2013, after the introduction crash testing and regulations on pedestrian protection, 97% of cars received at least a 3-star rating (Strandroth et al., 2014). These improvements in vehicle design were driven by competition generated by pedestrian testing by Euro NCAP starting in 1997 and a two-tier vehicle design regulation that went into effect in 2004, with tier-one compliance required by 2013. The pedestrian safety performance of cars sold in the USA and India is unknown because these countries do not conduct pedestrian NCAP tests. Therefore, we estimated the reduction in injury burden under various scenarios of the pedestrian safety performance of the current vehicle fleet. For the primary result reported in this paper, we assumed that the pedestrian star ratings of the vehicle fleet in the USA in 2013 were comparable to the situation in Germany in 1997 (pre-regulation and pre NCAP) – i.e. we assumed that the evolution of pedestrian friendly vehicle designs is driven primarily by design regulations and consumer testing. For the primary result for India, we assumed that all cars sold in India would have received a 0-star rating for pedestrian safety, given the poor results from occupant crash testing for selected cars in India (Global NCAP, 2015). Figure A2 (see appendix) shows the star rating distribution that was assumed for each country in 2013 (Global NCAP, 2015; Strandroth et al., 2014). We obtained probabilities of death and injury for a pedestrian hit by a car for each star rating (Pastor, 2013; Strandroth et al., 2014). The reduction in deaths was modeled as a corresponding increase in the number of non-fatal injury cases. Thus, we computed the percentage reduction in deaths, injuries and DALYs lost in Germany, US, and India if all cars had at least a 3-star rating (see appendix for a detailed description of analytical steps).

HMVs: Due to a lack of real-world data regarding the effect of improved HMV design, we used estimates from computer simulation studies to estimate the potential benefit of inserting retrofittable, energy-absorbing front on all HMVs in each country. Several studies have investigated the effect of improved HMV design on pedestrian injuries

through simulations (Chawla et al., 2000; Feist et al., 2008; Lakshminarayana et al., 2011; Ramli & Yamazaki, 2011; Ramli & Yamazaki, 2012; Yamazaki & Ramli, 2013) Most of these studies are limited in that they do not consider secondary ground impacts, despite that secondary impacts have been shown to cause a large proportion of the injuries (Otte & Pohlemann, 2001). Lakshminarayana et al. demonstrate that the effect of an energy-absorbing front in reducing pedestrian injuries may vary greatly according to the speed of the vehicle, although this was not captured in analysis (Lakshminarayana et al., 2011). In our analysis, we used data from Feist el al. because they simulated the effect of a relatively simple, seemingly-efficacious, energy-absorbing front at 40km/h (the test speed used in pedestrian protection testing (Hutchinson et al., 2012)) (Feist et al., 2008). This estimate was discounted by 31% to take into account that adding an energy-absorbing front would likely not reduce some deaths and injuries due to secondary impact with the ground (Otte & Pohlemann, 2001) and was further discounted to take into account that some deaths and injuries occur where the first point of contact with the pedestrian is not the front of the vehicle (Jermakian & Zuby, 2011; Knowles et al., 2012) (see appendix). This modified percent reduction was applied to the estimated number of pedestrian deaths due to collision with an HMV in 2013. A reduction in deaths was modeled as a corresponding increase in injuries. These revised death and injury counts were then used to estimate the DALYs lost if HMVs had been designed better (see appendix). We did not account for reductions in non-head injuries because head injuries comprise the majority (85%) of serious injuries in pedestrians (Crandall et al., 2002).

Sensitivity Analysis

We performed a sensitivity analysis to study the effect of varying the assumed star ratings distributions of the vehicle fleets in USA and India in 2013. We assessed the burden of injuries for each of these countries for the following scenarios: all cars have a pedestrian star rating of zero stars; pedestrian star ratings of the vehicle fleet comparable to the situation in Germany in 1997; a pedestrian star rating distribution that is midway between Germany in 1997 and Germany in 2013; and pedestrian star ratings comparable to the situation in Germany in 2013. We also estimated the deaths that would have occurred in Germany 2013 had cars not improved in terms of passive pedestrian protection.

Baseline estimates for pedestrian deaths and injuries in India have substantial uncertainty. Therefore, we also estimated the effect of using the lower bound and upper bound of the uncertainty interval of the GBD estimates for pedestrian deaths in India.

Finally, we estimated the effect of improving car design to make all cars have a 4-star rating using the same methods as previously described. The use of external airbags for pedestrian protection is one way that may enable cars to achieve a 4-star rating (Jakobsson et al., 2013).

RESULTS

While pedestrians comprise the largest share of DALYs lost in India, motor vehicle occupants contribute the most in the US and Germany (Fig. 1a). Pedestrians account for 37% of DALYs lost in India, compared to 11% in the USA

and 10% in Germany. More broadly, road users that stand to benefit from softer vehicle fronts – i.e. pedestrians, bicyclists, and motorcyclists – account for about two-thirds of the traffic injury burden in India (68% of deaths; 66% of DALYs) but much lower proportions in the US (31% of deaths, 27% of DALYs) and Germany (47% deaths, 39% DALYs).

Most pedestrians are struck by cars in Germany and the USA, whereas in India pedestrians are also frequently involved in crashes with HMVs and motorized two-wheelers (Fig. 1b). Crashes with cars account for 88% and 74% of the DALYs lost by injured pedestrians in the USA and Germany, respectively, compared to only 22% in India. In contrast, crashes with HMVs account for 41% of DALYs lost by pedestrians in India, compared with only 10% in the USA and 20% in Germany. Crashes with motorized two-wheelers are rare in the USA and Germany (1% of DALYs) but account for 29% of DALYs in India.

DALYs lost by pedestrians per 100,000 population in 2013 was highest in India, and lowest in Germany (see appendix, Fig. A3). Notably, the rate of DALYs lost by pedestrians struck by HMVs in India is more than 20 times that in the USA and Germany. The rate of DALYs lost by pedestrians struck by cars in India and the USA was 3 times and 2.6 times that in Germany, respectively.

If car designs were improved to have at least a 3-star pedestrian safety rating, India and the USA would see large benefits (Table 1; see appendix, Fig. A3). In Germany, where 97% of cars already have a 3-star or better rating (see appendix, Fig. A2), further improvement will lead to only small reductions (2% in deaths; and a 1% reduction in DALYs) in the health loss of pedestrians struck by cars. In India, where we assumed that all cars currently have a 0-star rating, improvements to a 3-star threshold will lead to a 46% reduction in deaths and a 41% reduction in DALYs lost by pedestrians struck by cars. In the US, where we assumed that currently 30% of cars have a 0-star rating and 70% have a 1-star rating, improvements will result in a 27% reduction in deaths and 24% reduction in DALYs lost by pedestrians struck by cars. Improvements in design of HMV fronts, which are excluded from pedestrian safety regulations and NCAP testing worldwide, will lead to substantial reductions in deaths (16%) and DALYs (approx. 20%) lost by pedestrians in HMV impacts in all three countries.

Compared to all RTIs in each country, improved car design would have been expected to decrease the DALYs lost by 0.2%, 3.7%, and 3.3% in Germany, USA, and India, respectively. Inserting an energy-absorbing front onto HMVs would have been expected to decrease the DALYs lost by 0.6%, 0.3%, and 3.3% in Germany, USA, and India, respectively (Fig. 2). Thus, the net impact of vehicle design for pedestrian safety in each country is governed by: (1) the frequency of pedestrian involvement in crashes, (2) the types of vehicles that strike pedestrians, and (3) the safety design of these vehicles.

Sensitivity Analysis

If we assume that that in 2013 the car fleet in the USA was similar in terms of star ratings to Germany in 2013, further improvements in car design would have resulted in a 1.5% reduction in DALYs lost by pedestrians hit by cars compared with 24.3% in the base case discussed above (see appendix, Table A3). Similarly, for India, assuming that the car fleet in 2013 was similar to Germany in 1997, there would have been a 20% reduction in DALYs lost by pedestrians hit by cars (compared with 41.0% in the base case). Figure 3 illustrates how varying the assumed vehicle fleet star ratings influences the predicted reduction in DALYs lost from road traffic crashes. Notably, if we assume that the US vehicle fleet in 2013 has a pedestrian star rating that is mid-way between the situation Germany in 1997 and 2013, then further improvements would lead to reductions of 2.4% of the total road traffic DALYs. Similarly, if we assume that the Indian vehicle fleet is comparable to Germany in 1997 then further improvements would lead to reductions of 2.0% in road traffic DALYs. If Germany had not undergone improvements in car design for pedestrian safety between 1997 and 2013, we predict that an additional 152 pedestrians would have been killed by cars.

The effect of varying the estimate of the number of pedestrian deaths in India in 2013 (i.e. using the upper/lower bounds of the 95th UI reported by GBD) is reported in Table A4 (see appendix). The reduction of pedestrian deaths by improving car design ranges from 6,458-17,676, compared to a reduction of 4,192-11,475 deaths by improving HMV design.

If all cars achieved at least 4 stars for pedestrian safety instead of 3 stars, it would result in greater reductions in DALYs lost in each country (see appendix, Fig. A5). Compared to all RTIs in each country, requiring cars to have at least a 4-star rating would have been expected to decrease the DALYs lost by 5.1%, 13.1%, and 8.9% in Germany, USA, and India, respectively.

DISCUSSION

In the 1950 and 60s, the US led the way by creating a paradigmatic shift in road safety that put car design at the center stage (MacLennan, 1988). Previously, road safety had been primarily viewed as a problem of bad drivers, and interventions had focused, usually unsuccessfully, on reducing risky behaviors. During this period, however, a coalition of engineers, ER doctors, lawyers, and Congressional representatives created a political movement that led to the passage by the US Congress of the Motor Vehicle Safety Act of 1966. The Act focused on the vehicle, not the driver, as the target for change. Federal regulations were promulgated that regulated the safety design features of automobiles. In 1978, the US NCAP became the first government program in the world to provide consumers information about the relative safety of vehicles and to establish market forces to encourage manufacturers to sell safer cars (Hershman, 2001). A large body of literature has investigated how the resulting changes in vehicle design have improved safety of occupants (Farmer & Lund, 2015; Farmer, 2005; O'Neill, 2009; Robertson, 1981; Wenzel, 2013). According to the National Highway Traffic Safety Administration, improvements in vehicle technology have saved an estimated 328,551 lives between 1960 and 2002 (Kahane, 2004).

Unfortunately, regulations and NCAP testing in the US have focused primarily on occupant safety. In contrast, Euro NCAP started pedestrian testing in 1997 and a European directive was adopted in 2005 to regulate vehicles for pedestrian protection in 2005. These have resulted in a large increase in the proportion of cars in Europe that had a high pedestrian star rating. Analysis of real-world crash data suggests that these newer cars have substantially reduced the risk to pedestrians in Europe (Strandroth et al., 2011). Our analysis suggests that if the US had followed the same path as Europe, the health loss due to car-pedestrian crashes could have been substantially lower. Therefore, it is important that NHTSA is encouraged to adopt the proposed upgrades (NHTSA, 2016) to NCAP that include pedestrian testing. Simultaneously, it is important to educate customers about NCAP ratings for pedestrian safety so that they might take these into consideration when purchasing a vehicle, thereby creating a market incentive for motor vehicle companies to improve vehicle design for pedestrian safety.

LMICs like India will see the largest gains from improving vehicle front designs. India is expected to launch its NCAP in 2017 but the program will focus on occupant safety ignoring pedestrian protection (Automotive Industry Standards Committee, 2010). The Global NCAP program, which has been testing cars from India, also does not conduct pedestrian tests on these cars. However, vehicle occupants account for only 30% of traffic deaths in India. Furthermore, passenger cars, which are the focus of NCAP testing, account for far fewer deaths (approximately 10%) (Bhalla et al., 2016). In contrast, pedestrians account for 42% of traffic deaths in India. Pedestrians, bicyclists, and motorcyclists, who stand to benefit from softer vehicle fronts, together account for over two-thirds of traffic deaths. Thus, it is important that NCAP testing programs appropriately prioritize the needs of local population.

There are many factors that affect how much a country will benefit from vehicle front-end design for pedestrian safety. At the broadest level, these include the frequency with which pedestrians are struck by vehicles, the types of vehicles that strike pedestrians, and the safety design of these vehicles. Advanced engineering solutions, such as automatic braking, are also important for improving pedestrian safety. Our analysis highlights that it is important that all relevant types of vehicles are targeted for design improvements. Bus and truck fronts are usually excluded from regulations and NCAP testing. Yet, in India these are the vehicles that cause substantial morbidity and mortality for pedestrians. Several simulations studies show that energy-absorbing bus and truck fronts can substantially reduce injuries to pedestrians (Chawla et al., 2000; Feist et al., 2008; Lakshminarayana et al., 2011). Similarly, a motorized two-wheeler is the impacting vehicle in a large proportion (22%) of pedestrian deaths in India. However, there is little research aimed at understanding motorcycle-pedestrian crashes and mitigating their effects.

One of the major limitations of our study is that the risk associated with the current vehicle fleet in India and the US is poorly understood. Therefore, we have provided estimates of the reductions in health loss that are possible under varying assumptions of the safety of the current vehicle fleet. For the USA, we expect that the car fleet in 2013 was comparable to the car fleet in Germany in 1997. This is supported by the results of a study of seven small cars (model years 2002-2007) in the US that were subjected to Euro NCAP style pedestrian head form tests (Mueller et

al., 2013). For India, we expect that the current car fleet would receive zero stars. Although there is no empirical evidence on pedestrian safety performance, Global NCAP's test of Indian cars for occupant safety show very poor outcomes (Global NCAP, 2015). Another limitation of our study is that the only evidence on the effectiveness of pedestrian safety design is from relatively small studies that look at correlation between star ratings and injury outcomes, which may overestimate benefits (Pastor, 2013; Strandroth et al., 2014). On the other hand, our analysis underestimates the benefits of vehicle front-end design because it does not assess impact on other vulnerable road users, such as cyclists, who may experience reduced injury risks from softer vehicle fronts.

Improving vehicle designs for protecting pedestrians is important. In LMICs, pedestrians are the most common victims of traffic crashes. However, even in the US the proportion of pedestrians killed in traffic crashes has steadily increased from 11% in 2005 to 15% in 2014 (Retting & Rothenberg, 2016). In 2015, pedestrian death toll by in the US increased by 9.5% to 5376 deaths and are now at the highest level in the last 20 years (National Highway Traffic Safety Administration, 2016). While the reasons for this increase remain poorly understood, it underscores the need to prioritize pedestrian safety including through vehicle design in the US. Globally, cars designs are regulated for pedestrian safety in only 44 countries, most of which are high-income European countries (WHO, 2015). In Africa, only South Africa, has such regulations. Pedestrians are often the poorest and vulnerable users of roads globally. Protecting them should be an urgent priority.

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Table 1. The impact of improving vehicle pedestrian safety ratings on burden of pedestrian injuries in each country

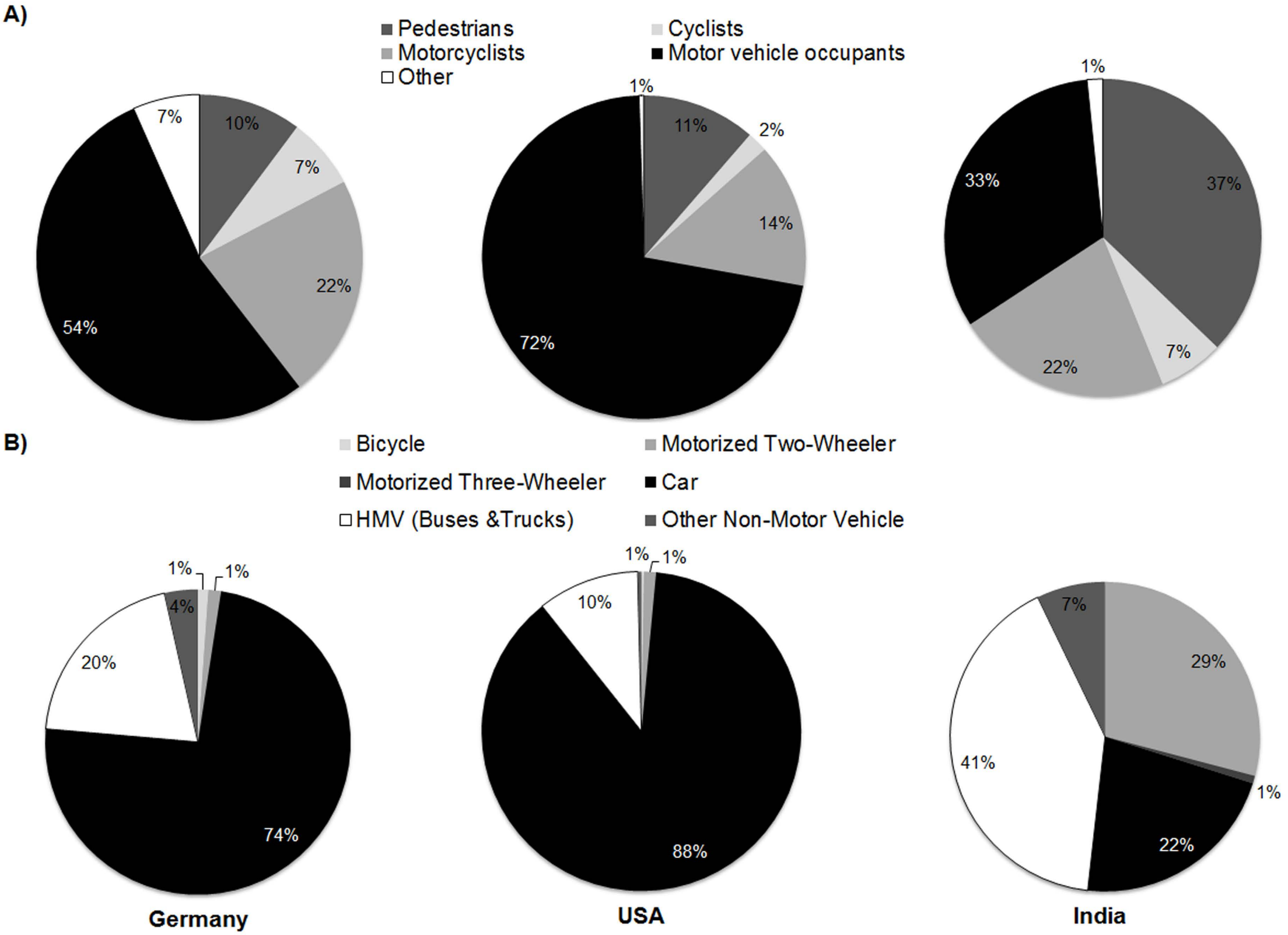
Vehicle	Scenario	Deaths			DALYs		
		Germany	USA	India	Germany	USA	India
All RTIs	Baseline (N)	2605	23142	264348	129547	1214336	14411349
	Baseline (per 100,000)	3.2	7.3	20.7	161	383	1126
Pedestrians hit by cars	Before improved design	412	4160	24576	14636	190880	1198899
	After improved design	405	3039	13275	14429	144472	707449
	Percent reduction	2%	27%	46%	1%	24%	41%
Pedestrians hit by HMVs	Before improved design	112	487	46024	3976	22365	2245211
	After improved design	94	410	38688	3171	18103	1803109
	Percent reduction	16%	16%	16%	20%	19%	20%
Pedestrians hit by cars & HMVs	Before improved design	524	4647	70600	18611	213245	3444110
	After improved design	499	3449	51962	17599	162575	2510557
	Percent reduction	5%	26%	26%	5%	24%	27%

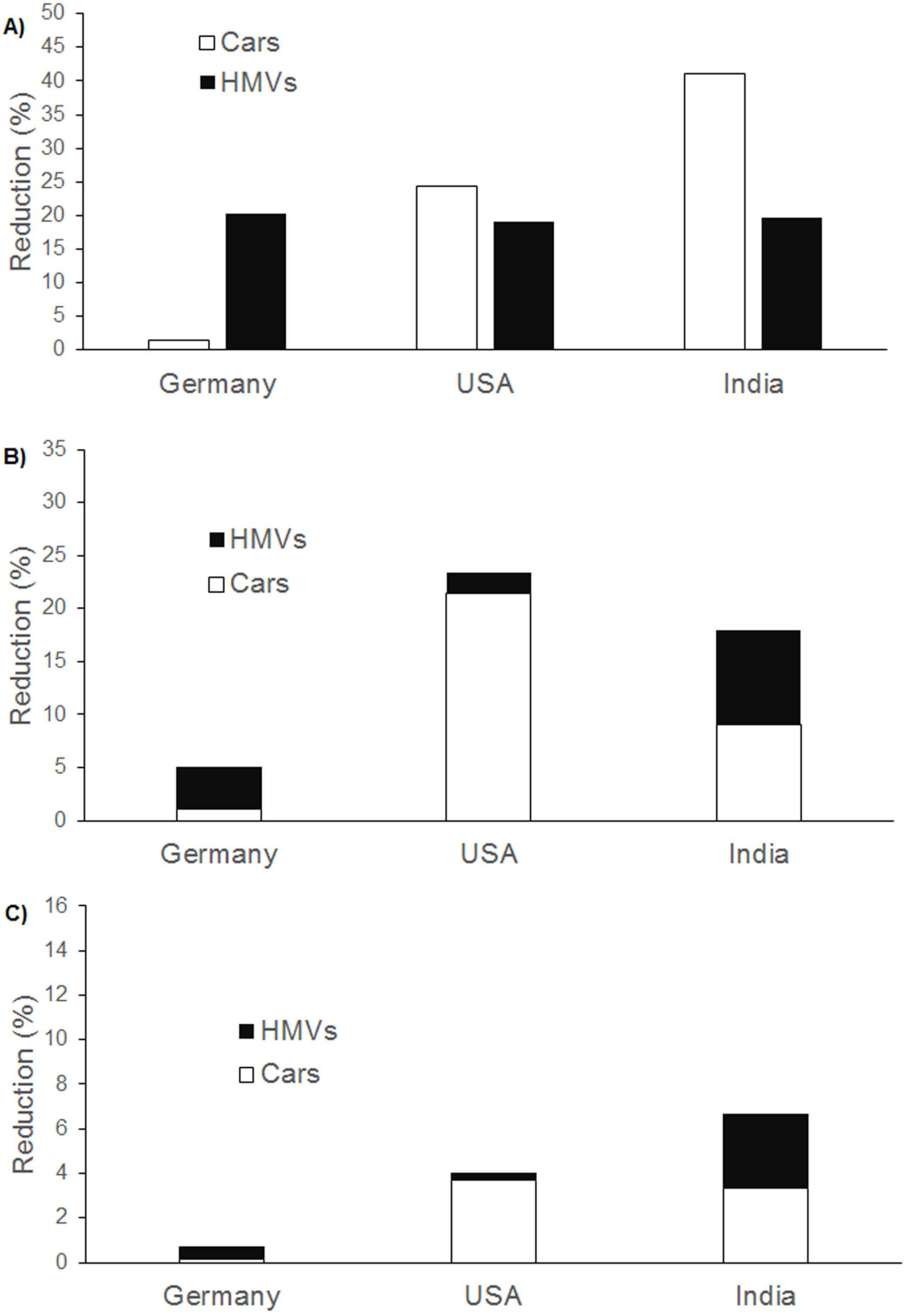
FIGURE LEGEND

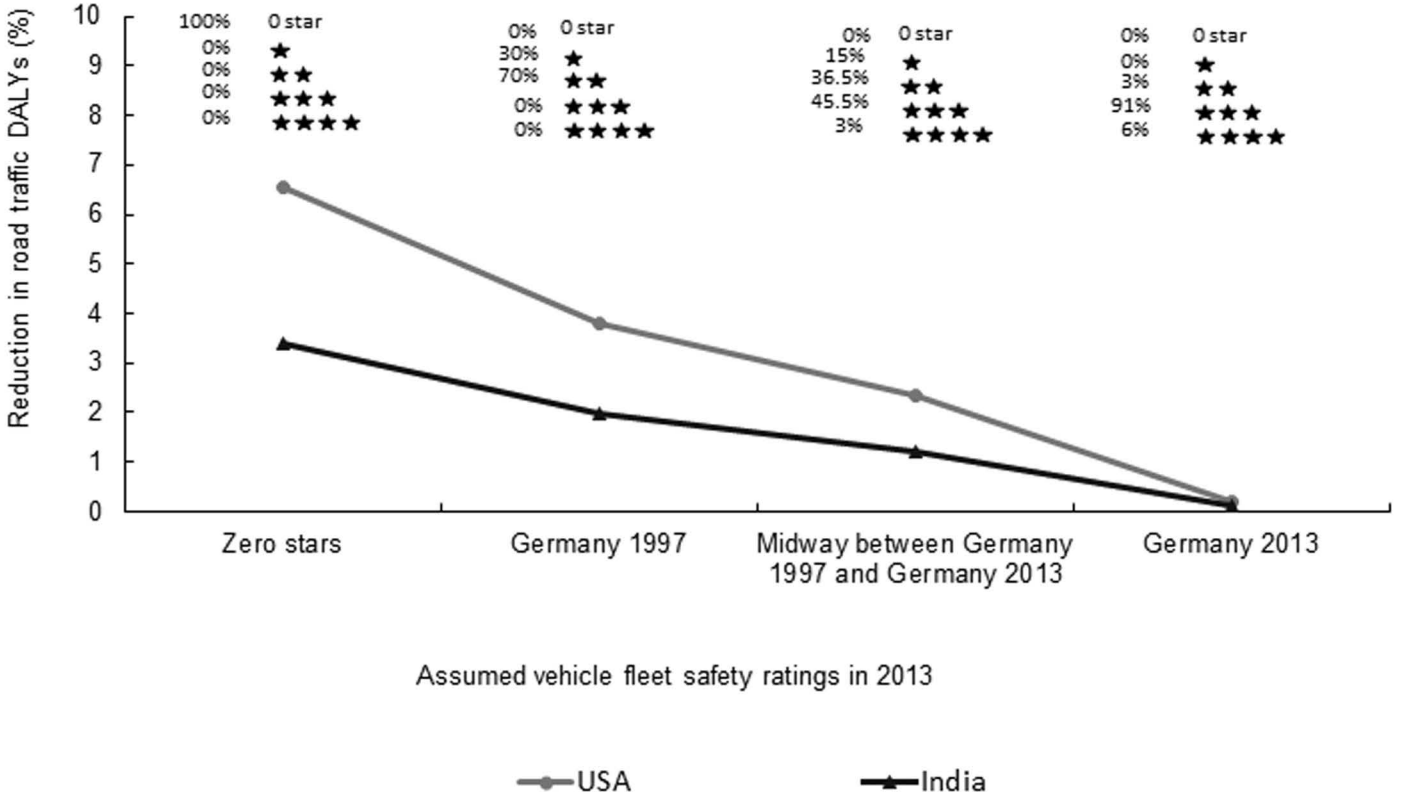
Figure 1. Percentage breakdown in each country of a) DALYs lost by road user in 2013 and b) Pedestrian DALYs lost in crashes with different types of vehicle

Figure 2. The percentage reduction in DALYs after improved vehicle design relative to a) all pedestrians hit by either a car or HMV, b) all pedestrians, and c) all RTI victims

Figure 3. Reduction in road traffic DALYs with varying assumptions of current (baseline) safety rating. Zero Stars assumes that all cars in the vehicle fleet would currently receive zero EuroNCAP stars; German 1997 corresponds to the mix of star ratings in the vehicle fleet of Germany in 1997 (Strandroth et al., 2014); Germany 2013 corresponds to the mix of star ratings in 2013 (Strandroth et al., 2014); Midway corresponds to an averaged state between 1997 and 2013 in Germany.


A)
Pedestrians
Cyclists
Motorcyclists
Motor vehicle occupants
Other
10%
7%
22%
54%
7%
1%
11%
2%
14%
72%
1%
37%
7%
22%
33%
B)
Bicycle
Motorized Two-Wheeler
Motorized Three-Wheeler
Car
HMV (Buses &Trucks)
Other Non-Motor Vehicle
1%
1%
4%
20%
74%
1%
1%
10%
88%
7%
29%
41%
1%
22%
Germany
USA
India


A)
Cars
HMVs
Reduction (%)
0
5
10
15
20
25
30
35
40
45
50
Germany
USA
India
B)
HMVs
Cars
Reduction (%)
0
5
10
15
20
25
30
35
Germany
USA
India
C)
HMVs
Cars
Reduction (%)
0
2
4
6
8
10
12
14
16
Germany
USA
India


Reduction in road traffic DALYs (%)
10
9
8
7
6
5
4
3
2
1
0
100%
0 star
0%
0%
0%
0%
0%
0 star
30%
70%
0%
0%
0%
0 star
15%
36.5%
45.5%
3%
0%
0 star
0%
3%
91%
6%
Zero stars
Germany 1997
Midway between Germany 1997 and Germany 2013
Germany 2013
Assumed vehicle fleet safety ratings in 2013
USA
India

Supplementary Appendix

Contents

Methodological Considerations

Reduction in deaths – Cars

- The probabilities of death corresponding to the star ratings were obtained from analyzing documented car to pedestrian crashes, where each additional point in the NCAP score (on a scale from 0-36) confers a 2.5% lower probability of death, and a NCAP score of 22 is associated with a 0.37% probability of death. The probabilities of death for each NCAP score within a star rating category were averaged to yield a probability of death for each star rating[16].
- The reduction in the probability of death was calculated by subtracting the weighted sum of the death probabilities after improved vehicle design from the weighted sum of death probabilities before improved vehicle design
- The percent reduction in deaths that would be expected by requiring all cars to have at least a 3-star rating for pedestrian safety was applied to the estimated number of deaths that actually happened in each country in 2013 to yield the estimated deaths that would have happened if the vehicle fleet was safer for pedestrians.
- It was assumed that the percent reduction in deaths would be the same for persons across all age-sex categories.
- The reductions in deaths were modeled as increases in injuries.

Reduction in injuries – Cars

- The reduction in injuries was calculated in a similar manner to the reduction in deaths. The probability of a MAIS 2+ injury was obtained for each star rating[17]. Linear extrapolation was used to estimate the probability of a MAIS 2+ injury for a 0-star car and a 4-star car.
- The reduction in the probability of injury was calculated by subtracting the weighted sum of the injury probabilities after improved vehicle design from the weighted sum of the death probabilities before improved vehicle design.
- The percent reduction of injuries was applied to the expected number of injuries in 2013 plus the added injuries owing to the reduction in deaths.

Reduction in deaths – HMVs

- The Head Injury Criteria (HIC) scores were compared for a HMV front with or without a SBS (safety bar with plastic-steel structure) using a MADYMO model at a speed of 40km/h[5]. A head risk injury curve was used to convert the HIC score into the probability of having a head injury with an AIS score of 2-6[11, 13]. Below are the equations that were used to convert from HIC to AIS score.

$$AIS\ 2=1/(1+EXP((2.49+(200/HIC))-0.00483*HIC)) \quad (1)$$

$$AIS\ 3=1/(1+EXP(3.39+(200/HIC)-0.00372*HIC)) \quad (2)$$

$$AIS\ 4=1/(1+EXP(4.9+(200/HIC)-0.00351*HIC)) \quad (3)$$

$$AIS\ 5=1/(1+EXP(7.82+(200/HIC)-0.00429*HIC)) \quad (4)$$

$$AIS\ 6=1/(1+EXP(12.24+(200/HIC)-0.00565*HIC)) \quad (5)$$

- Data regarding the probability of death for each AIS score were used to calculate the overall probability of death from the HIC score[14]. The reduction in death was obtained by subtracting the probability of death with the SBS from the probability of death without it.
- The reduction in deaths was modified to take into account that 31% of injuries result from ground impacts[15] and that, in approximately 21% of deaths[8, 9], the front of the vehicle is not the first point of contact, because we assumed that having the SBS would not help in either of these situations.
- This revised reduction in deaths was then applied to the estimated pedestrian deaths in 2013. Those that were protected from dying were assumed to have been injured, and thus were added to the injury total.

Reduction in head injuries – HMVs

- The estimated reduction in head injuries by inserting the SBS was calculated by comparing the difference in probability of a pedestrian having an AIS 2 head injury using the same method as was used for deaths.
- The reduction in head injuries was modified to take into account that 31% of injuries result from ground impacts[15] and that, in approximately 29% of injuries[8], the front of the vehicle is not the first point of contact.
- The burden calculator was modified such that the probability of having a skull fracture or a minor, moderate, or severe traumatic brain injury was reduced by the calculated value for the reduction in head injuries.
- The revised death and injury counts were inserted into the burden calculator (altered to reflect a reduced probability of head injury) to calculate the DALYs lost in 2013 had HMVs been equipped with energy-absorbing fronts.

Tables

Table A1. List of the most important assumptions that were used in the study

Number	Assumption	Justification	Source
Nature of striking vehicle			
1	Who-hit-whom matrix data that were collected in one district in India are representative of all of India	Lack of a reliable nationwide source of who-hit-whom data available	[1]
2	The ratio of non-fatal to fatal injuries among pedestrians does not vary by striking vehicle	No reliable data available to adjust for this issue	[2]
3	The relationship between improved design and pedestrian outcome is not modified by speed.	Improved design has shown to be similar at low and high vehicle speeds	[17]
Age-sex variations			
4	The ratio of non-fatal to fatal injuries varies similarly by age and sex for pedestrian road traffic injuries compared to all injuries	No data available on non-fatal to fatal injuries by age and sex for road traffic injuries	[4]
5	Improvements in vehicle design would decrease fatality rates independent of age and sex	No data available to adjust for age and sex	
Cars			
6	USA had the same pedestrian star ratings distribution in the car fleet in 2013 as Germany had in 1997	Limited data was available for the USA during this time; the USA does not regulate pedestrian star ratings for cars; and Germany 1997 represents a time just before regulation was introduced in Germany	[12, 17]
7	All cars in India in 2013 would have received 0 stars for pedestrian safety	Global NCAP found that most Indian cars would have received 0 stars in occupancy crash testing in 2013, and it was assumed that they would have performed just as poorly, if not more poorly, in pedestrian crash testing	[6]
8	Along with incorporating other design changes, installing external pedestrian airbags on cars would result in the car receiving 4 stars	Results from simulation studies suggest this would be the case	[7]
9	Probability of death for a pedestrian hit by a 0-star or a 4-star car was calculated through extrapolation from data from cars with pedestrian ratings of 1-3 stars	No real-world data from cars with 0 or 4 stars; significant correlation between NCAP score and probability of death was found	[16]
10	Probabilities of MAIS2+ injuries vary by pedestrian star rating to the same degree as probabilities of all non-fatal injuries	No real-world data available on how the probability of any non-fatal injury varies with pedestrian star rating	[17]
HMVs			
11	Only injuries to the head would be reduced with improved HMV design.	Incomplete data available on reductions for other injury types	[5]
12	The reduction in head injuries and deaths at 40km/h is representative of the real world	Crash testing is typically conducted at 40km/h, but speed of the vehicle can dramatically influence the estimated reduction in injury	[10]
13	Impact with the ground contributes to 33% of all types of injuries experienced by pedestrians after they are hit by a vehicle	Real-world findings	[15]
14	The probability of being injured by the front of the vehicle is same for cars and HMVs	Limited data available specifically for HMVs	[8]
Other			
15	An injured pedestrian can have only one injury	Burden calculator is not account for multiple injuries	[3]

Table A2. Baseline burden of disease in each country by impacting vehicle type

	Counts				Per 100,000			
Vehicle Type	**Deaths**	**YLLs**	**YLDs**	**DALYs**	**Deaths**	**YLLs**	**YLDs**	**DALYs**
Germany								
Bicycle	6.15	155.63	62.82	218.44	0.01	0.19	0.08	0.27
Motorized Two-Wheeler	7.38	186.75	75.38	262.13	0.01	0.23	0.09	0.33
Motorized Three-Wheeler	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Car	411.91	10426.94	4208.78	14635.73	0.51	12.94	5.22	18.17
Heavy Transport (Buses/Trucks)	111.89	2832.39	1143.28	3975.67	0.14	3.52	1.42	4.93
Tractors	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Other Non-Motor Vehicle	19.67	498.00	201.02	699.02	0.02	0.62	0.25	0.87
Total	557.00	14099.71	5691.28	19791.00	0.69	17.50	7.06	24.56
USA								
Bicycle	11.94	432.97	114.74	547.72	0.00	0.14	0.04	0.17
Motorized Two-Wheeler	57.70	2092.71	554.59	2647.30	0.02	0.66	0.17	0.83
Motorized Three-Wheeler	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Car	4160.04	150891.76	39987.80	190879.55	1.31	47.58	12.61	60.19
Heavy Transport (Buses/Trucks)	487.43	17679.81	4685.32	22365.13	0.15	5.57	1.48	7.05
Tractors	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Other Non-Motor Vehicle	17.91	649.46	172.11	821.58	0.01	0.20	0.05	0.26
Total	4735.00	171746.72	45514.57	217261.28	1.49	54.16	14.35	68.51
India								
Bicycle	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Motorized Two-Wheeler	32619.00	1191498.53	399767.55	1591266.08	2.55	93.12	31.24	124.37
Motorized Three-Wheeler	893.67	32643.80	10952.54	43596.33	0.07	2.55	0.86	3.41
Car	24575.96	897704.37	301194.73	1198899.10	1.92	70.16	23.54	93.70
Heavy Transport (Buses/Trucks)	46024.07	1681155.46	564055.58	2245211.04	3.60	131.39	44.08	175.48
Tractors	8043.04	293794.16	98572.82	392366.98	0.63	22.96	7.70	30.67
Other Non-Motor Vehicle	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	112155.75	4096796.31	1374543.22	5471339.52	8.77	320.19	107.43	427.62

Table A3. Assessing the impact of varying the baseline estimate of car-fleet star-ratings on burden of pedestrian injuries in each country

Scenario	Pedestrian Deaths		Pedestrian DALYs	
	USA	India	USA	India
Before improved design	4160	24576	190880	1198899
After improved design (assuming car fleet star ratings)				
Zero stars	2247	13275	111323	707449
Germany 1997	3039	17953	144745	913368
Midway between Germany 1997 and Germany 2013	3452	20395	162326	1021896
Germany 2013	4089	24158	188401	1181528

Table A4. Sensitivity analysis of the estimate of the number of pedestrian deaths in India in 2013

		Deaths			DALYs		
Vehicle Type	Scenario	Estimate	Lower Limit	Upper Limit	Estimate	Lower Limit	Upper Limit
Cars	Before improved design	24575.96	14043.67	38437.79	1198899.10	669485.26	1953598.77
	After improved design	13274.61	7585.63	20762.02	707448.51	414669.51	1154095.67
HMVs	Before improved design	46024.07	26299.96	71983.50	2245211.04	1253763.31	3658557.70
	After improved design	38687.59	22107.61	60508.95	1803108.75	1007340.85	2936179.73

Table A5. The impact of improving passenger car design for pedestrian safety on burden of pedestrian injuries in each country by making cars 4 stars

Scenario	Pedestrian Deaths/100,000			Pedestrian DALYs/100,000		
	Germany	USA	India	Germany	USA	India
Before improved design	0.51	1.31	1.92	18.17	60.19	93.70
After improved design	0.37	0.69	0.74	13.88	34.42	42.46
Absolute reduction	0.14	0.62	1.18	4.29	25.76	51.24

Figures

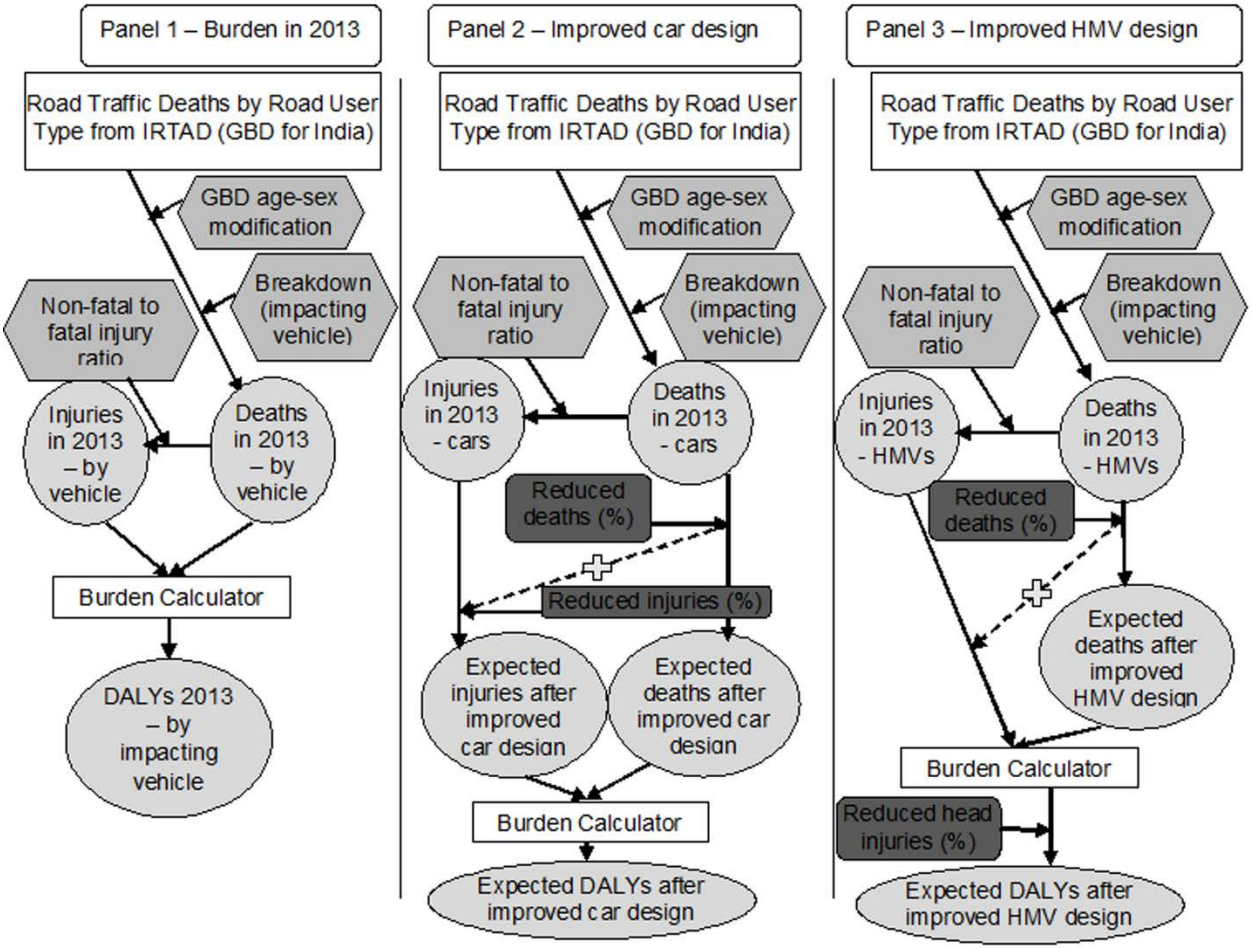
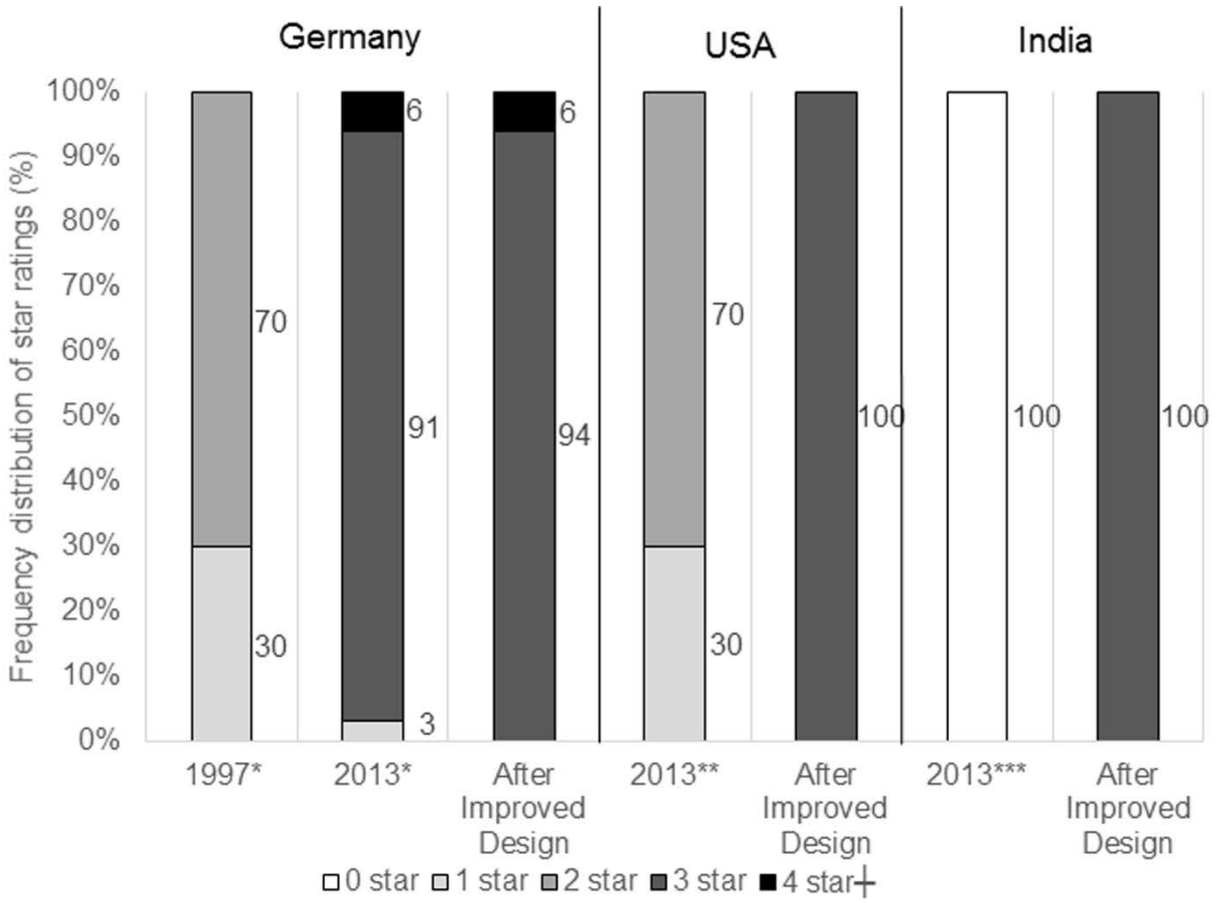


Figure A1. Flowchart of the methods used in this study



*Data obtained from Strandroth et al. 2014
**Assumed to be the same as Germany in 1997 (pre-regulation)
***All cars assumed to receive 0 stars, based on poor performance of India cars on Global NCAP occupant crash testing
┼0 star corresponds to a NCAP score of 0, 1 star to a score of 1-9, 2 star to a score of 10-18, 3 star to a score of 19-27, and 4 star to a score of 28-36.

Figure A2. Modeled distribution of car pedestrian star ratings in each country before and after improved vehicle design

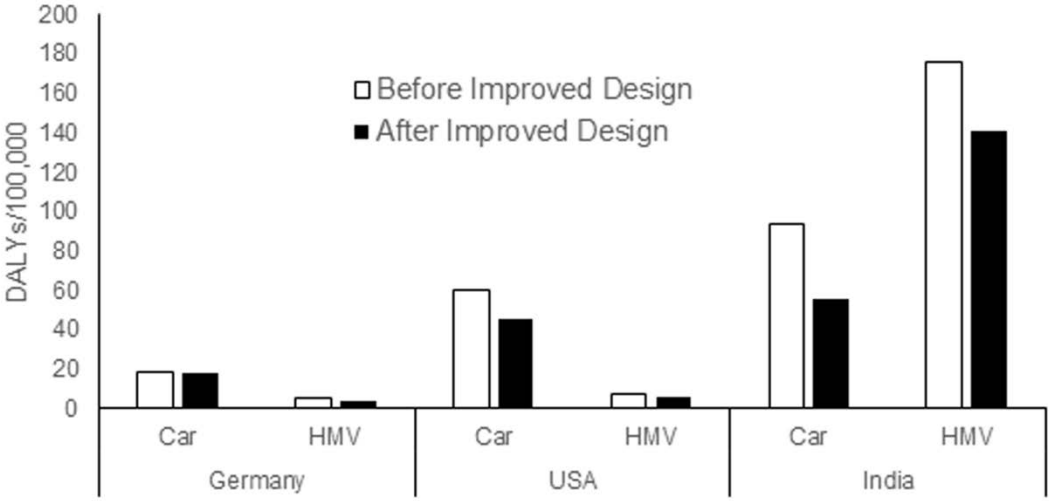


Figure A3. DALYs/100,000 lost by pedestrians hit by cars and HMVs in each country

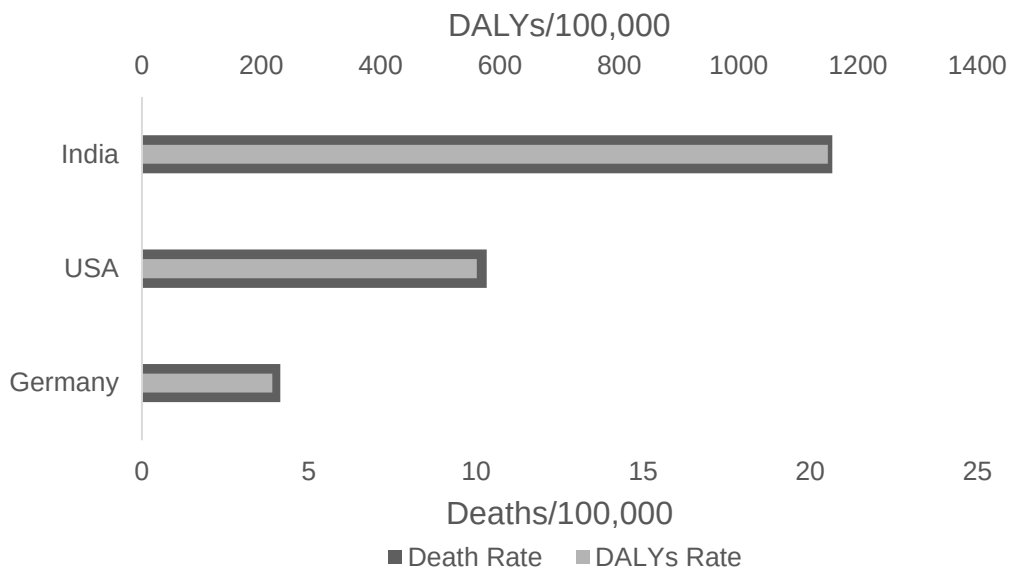


Figure A4. Deaths and DALYs per 100,000 due to RTIs in each country in 2013

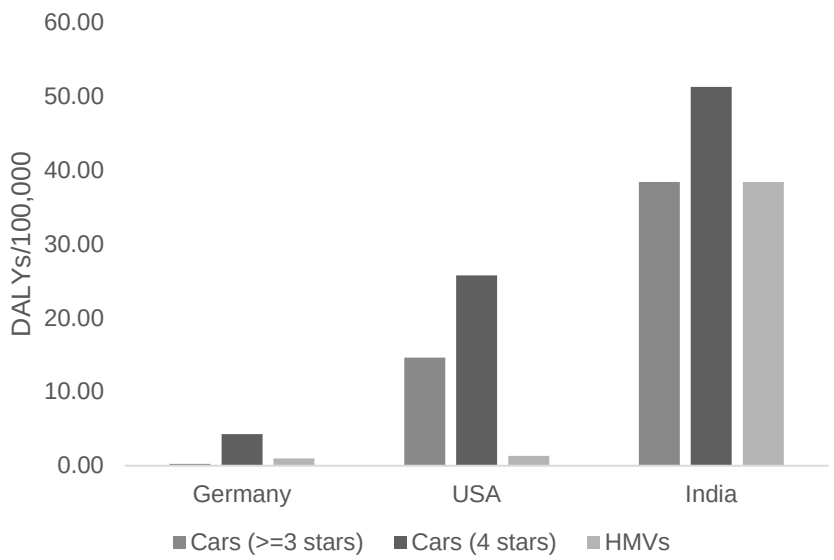


Figure A5. Comparison of the reduction of DALYs due to each design intervention in each country

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