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Missed prevention: global gaps in seat belt policy, monitoring, and road traffic mortality

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ABSTRACT

Objective: Seat belts are among the most effective interventions for reducing vehicle occupant fatalities, yet their global life-saving potential depends on their availability and use. This study documents and quantifies global gaps in seat belt governance and estimates the burden of preventable road traffic deaths associated with incomplete implementation. The analysis examines how the presence and maturity of seat belt laws and associated monitoring systems relate to population-level road traffic mortality.

Methods: Data from the World Health Organization's Global Status Report on Road Safety (2013, 2018, 2023) were combined with Global Health Estimates mortality data (2010, 2015, 2021). One hundred and eighty-three countries were classified according to the availability and standards of seat belts in vehicles, the scope and maturity of mandatory seat belt use legislation for drivers, front-seat occupants, and rear-seat occupants, and monitoring capacity. The relation between these and four-wheeler fatality rates was assessed in bivariate analyses. A counterfactual modeling framework estimated preventable deaths between 2011 and 2021 under two scenarios: (1) countries without long-standing comprehensive legislation achieving the seat belt wear rates observed in countries with more mature legislation, and (2) universal seat belt use globally. Sensitivity analyses varied seat belt effectiveness and vehicle occupancy distributions.

Results: Between 2011 and 2021, approximately 12.8 million road traffic deaths occurred globally. As of 2021, sixty-seven countries – encompassing about one quarter of the global population – did not legally require seat belt use in all seating positions. Increasing seat belt use in countries lacking mature legislation to the levels observed in countries with long-standing comprehensive laws could have prevented about 96,000 deaths over the study period (≈0.8% of global road traffic fatalities). Universal seat belt use could have prevented 557,000–1,140,000 deaths globally (≈4.3-8.9%). Monitoring capacity was limited: while ninety-nine countries (55% of the population) consistently reported the distribution of road traffic fatalities by user type, only 10 countries (4% of the population) consistently reported seat belt wear rates for all occupants.

Conclusions: Large disparities in seat belt legislation, equipment standards, and monitoring systems continue to limit the global effectiveness of this well-established safety intervention nearly 60 years after its development. Addressing these gaps rapidly is essential to advance the global road safety aspiration of eliminating these deaths.

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Introduction

Numerous studies have assessed the enormous burden of road traffic injuries (RTIs) globally; particularly, the death and disability-adjusted years loss in low- and middle-income countries and economic loss in high income countries (Murray et al. 1996; Dalal et al. 2013; Naghavi et al. 2025). Global road traffic fatalities (RTFs) in 2021 were almost the same as in 2000 – just below 1.2 million. In 2021, RTFs remain a significant contributor to global deaths, which ranked as the 14th leading cause, and the top one for youth aged 5–29 years (WHO 2023; Global Health Estimates 2024). Four-wheel vehicle (4Ws) occupants accounted for 25% of road fatalities in 2021, representing almost 300,000 deaths among road users who benefit the most from advanced vehicle crashworthiness and restraint systems (WHO 2023).

Since the early twentieth century, global motorization expanded rapidly, rising from fewer than 1 million vehicles in 1910, predominantly in the USA, to approximately 500 million worldwide by 1985 and exceeding 1 billion in 2021 (McNeill 2001; WHO 2023). This growth of vehicle fleet went hand in hand with an increase in RTFs. Early road traffic incidents mainly involved single-vehicle crashes or collisions with fixed objects or pedestrians; however, as motor vehicle density increased, multi-vehicle collisions

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became more frequent (Borowy 2013). By the mid-twentieth century, growing public and scientific concern regarding vehicle safety deficiencies led to larger efforts to improve occupant protection. In 1959, Nils Bohlin presented the modern three-point seat belt under an open patent. In 1967, he reported substantial reductions in injury frequency and severity among more than 28,000 crash cases involving belted occupants (Bohlin 1967). Improvements in vehicle safety features continued steadily thereafter, and seat belt effectiveness was repeatedly evaluated in experimental crash testing and observational studies. Extensive research has consistently demonstrated that seat belts are the most effective fatality-preventing passive safety intervention, with reported fatality risk reductions ranging from 40 to 75% compared with unbelted occupants (Viano 1991; Evans 1996; Crandall et al. 2001; Cummings 2002; Zhu et al. 2007).

Not long after the 1967 publication of Bohlin's work, high-income countries' (HIC) governments started passing laws mandating the installation of seat belts as standard equipment in vehicles (Milne 1985). Further, international standards on this equipment were developed (United Nations 1976; 1985). The public, however, was not immediately persuaded by the significant safety benefits associated with seat belt use; instead, many were concerned about the inconvenience and discomfort it entailed. Since voluntary seat belt wear rates in HICs were only between 10 and 40% (Berard-Andersen 1979; Mackay 1985), some authorities implemented additional measures to increase seat belt wear rates. These efforts relied primarily on public education campaigns and incentives, the implementation of mandatory seat belt use laws, and the enforcement of penalties for occupants who failed to comply (Dussault 1990; Maekinen and Hagenzieker 1991; Vasudevan et al. 2009). Alongside, other road safety measures were further implemented in some countries, including various behavioral and medical interventions, infrastructure changes and motorized vehicle safety features (Robertson 1996). The efforts proved effective: between 1975 and 1998, RTI occurrence and mortality significantly decreased in most HICs (Peden et al. 2004). However, low and middle-income countries (LMICs) showed continued increases in RTFs (Kopits and Cropper 2003). Such trends persist today: 92% of RTFs occur in LMICs, where 26-32% of fatalities are vehicle occupants in countries where this information is available (WHO 2023). This disparity has been attributed to gaps in the implementation of evidence-based interventions: vehicle and equipment standards, infrastructure, legislation targeting behavioral factors, as well as the availability of adequate post-crash care (Bachani et al. 2017).

Several studies have shown that higher seat belt wear rates are associated with reduced RTFs and that comprehensive, well-enforced legislation has been the most effective strategy for increasing seat belt usage (Abbas et al. 2011). However, out of 194 countries invited to participate in the last WHO Global Status Report on Road Safety (WHO 2023), 170 reported having mandatory seat belt wear laws, yet in only 117 of them laws apply to all occupants of the vehicle. Furthermore, one-quarter of participating countries lack a penalty system for noncompliance with mandatory seat belt use laws (WHO 2023). Road traffic safety epidemiological research emphasizes the importance of consistent vehicle occupancy data collection to inform effective reduction strategies (Barrimah et al. 2012; Ma et al. 2012). Yet in 2021, fewer than one-third of countries worldwide had national data systems to monitor seat belt use (WHO 2023).

This dispersion in legislation scope, enforcement strength, and monitoring capacity suggests substantial inefficiencies in preventing vehicle occupant fatalities associated with gaps in seat belt governance – a burden that has not yet been comprehensively quantified. A recent global modeling study estimated that full implementation of evidence-based interventions targeting major road safety risk factors, including (but not limited to) seat belt use, could prevent more than 120,000 deaths annually worldwide (Vecino-Ortiz et al. 2022). These estimates, however, were based on pooled estimates of intervention effectiveness and did not explicitly assess country-level variation in legislative scope, enforcement, or observed wearing prevalence. The objective of this study is therefore to quantify the excess vehicle occupant mortality associated with gaps in seat belt availability, legislation scope, and observed seat belt use.

Methods

The study included the harmonization, processing, and analyses of publicly available WHO data, obtained from the Global Status Reports on Road Safety (GSRRS) and the Global Health Estimates (GHE) of "Deaths by cause, sex and country or area". Country-level population counts (aged ≥5 years, as children should be using other restraint systems) and road traffic fatality counts were obtained from the most recent Global Health Estimates (Global Health Estimates 2024). Data from GSRRS depended on their release year, but the variables of main interest were: (1) percentage of fatalities that occurred in 4Ws (RTF_4W), (2) mandatory seat belt use law presence (general and then for drivers, front-seat, rear-seat occupants), as validated by WHO legal team for every country (Murphy et al. 2025), and (3) seat belt wear rates by seating position by countries (WHO 2013; WHO 2019; WHO 2023).

The workflow utilized Python (version 3.11.14) with Jupyter Notebook and standard scientific computing libraries, including NumPy, pandas, SciPy, and Matplotlib.

Data harmonization and variable definitions

In June 2024, all six GHE releases of "Estimated deaths by cause, sex and country or area" (for years 2000, 2010, 2015, 2019, 2020 and 2021) were re-released due to changes in data and estimation methods (Global Health Estimates 2024). To maintain chronological accuracy between the combined datasets, it was possible to form three pairs of GSRRS and GHE data with no more than one year difference between paired datasets (GSRRS 2013-2018-2023 with GHE 2010-2015-2021, respectively). All GSRRS releases enclose data collected around two years prior to the publication of

reports, therefore the study period considered in this paper is 2011–2021.

GSRRS releases include data from 194 WHO Member States and two territories, while GHEs reports on 183 WHO member states and two territories. Thus, this study includes data for 183 WHO Member States and excludes territories. Henceforth, the term 'countries' refers to WHO Member States. The term 'population' or 'global population' refers to population aged 5 years or older in these 183 countries.

The related numeric variables used throughout the study are presented in Table 1. There, the variable origins (taken directly from the datasets or constructed) and associated abbreviations, if present, are described: hereafter, only variable abbreviations are used where suitable.

Descriptive analytical framework

Descriptive analyses were conducted to characterize global variation in seat belt governance, monitoring capacity, and associated road traffic fatality rate of 4W occupants (RFR_4W) across the study period. Country and population distributions by income group were summarized to contextualize legislative and monitoring coverage.

Legislation requiring seat belts to be installed as standard equipment in vehicles as of 2021 was assessed. Countries were classified according to whether seat belt installation was mandated for all seating positions, limited positions, or not required. National legislation on seat belt and anchorage standardization was checked for adherence to UNECE pertinent regulations. For each category, country prevalence, population coverage, and mean RFR_4W were calculated.

The prevalence of mandatory seat belt use legislation was quantified for each study year. Legislation was assessed at two levels: (1) country-level presence of mandatory seat belt use laws and (2) population coverage, defined as the proportion of the global population residing in countries with such legislation. Analyses were conducted both overall and separately for drivers, front-seat occupants, and rear-seat occupants. Legislative prevalence was then examined across income groups for each study year. The percentage of countries within each income group with mandatory seat belt legislation (general and seating-position specific) was calculated.

National reporting availability was assessed for (1) RTF_4W and (2) seat belt wear rates (drivers, front-seat occupants, rear-seat occupants). The results were summarized by income group and study year. Then countries were grouped according to seat belt wear-rate reporting patterns across the three GSRRS waves:

- Group 1.1: reporting wear rates for all occupants in all three waves;
- Group 1.2: reporting at least one wear-rate value in at least one wave;
- Group 1.3: never reporting wear-rate data.

Additionally, mean RFR_4W values were examined across these reporting groups for each study year.

Finally, selected components of the supporting legal framework were examined for 2016 and 2021, the years in which these indicators were available. These included: (1) presence of a penalty system for noncompliance with mandatory seat belt use laws and (2) the presence and type of exemptions to mandatory seat belt use laws.

Table 1. Numeric variables of the study.

Variable, unit	Variable abbreviation	Origin
Population, n	–	GHE
Road traffic fatalities, n	RTFs	GHE
Road fatality rate per 100,000 population	RFR	Constructed: *RTFs * 100,000 / Population*
Proportion of fatalities that occurred in four-wheelers, %	RTF_4W	GSRRS
Road fatality rate of four-wheeler occupants per 100,000 population	RFR_4W	Constructed: *RFR * RTF_4W*
Seat belt wear rates for drivers, %	SBR_d	GSRRS
Seat belt wear rates for front occupants, %	SBR_fo	GSRRS
Seat belt wear rates for rear occupants, %	SBR_ro	GSRRS
Average belted four-wheeler occupant, %*	AVG_SBR	Constructed: *0.7 * SBR_d+0.2 * SBR_fo + 0.1 * SBR_ro*

*All occupant seat belt wear rates for a country were combined into one variable, using a fixed distribution of occupants – 70% of drivers, 20% front occupants and 10% rear occupants (European Commission 2024; Uzawa et al. 2025). This variable represents the percentage of how many four-wheeler occupants are belted in vehicles, already accounting for occupant distribution.

Counterfactual analysis and mortality estimation

To build on the descriptive assessment of global seat belt governance, a counterfactual modeling framework was applied to estimate the number of vehicle occupant deaths potentially associated with incomplete implementation of seat belt legislation. The availability of harmonized data on legislative scope, monitoring indicators, and seat belt use across countries enabled the analysis to move beyond descriptive comparisons and to characterize differences in 4W occupant mortality across legislative contexts. The modeling contrasted countries with more comprehensive seat belt use legislation with those where such legislation was adopted only recently or could not be confirmed. Seat belt wear rates observed under mature legislative frameworks were used as empirically derived reference levels representing a realistic policy scenario, reflecting restraint use levels where basic legislative structures are already in place. These reference levels may also reflect broader socioeconomic and structural characteristics that differ across countries; they were not explicitly controlled for in the analysis. Universal seat belt use was evaluated separately as an upper-bound prevention scenario.

Data treatment

Both the reported RTF_4W and seat belt wearing rates were missing in a substantial number of entries. Additionally, in GSRRS 2023, some countries reported RTF_4W to be 0%; if

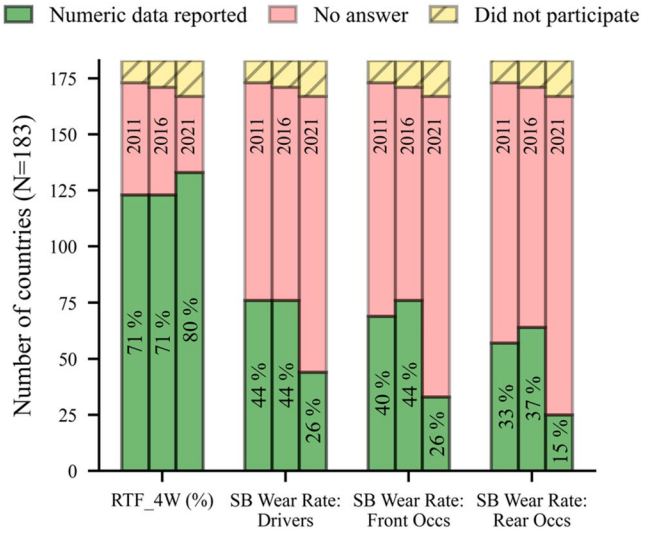

Figure 1. Availability of reported four-wheeler fatalities and seat belt wear data by year.

the corresponding country exceeded 10 fatalities, this value was considered implausible and was treated as missing too. The availability of data (and percentages) across study variables and reporting years is presented in Figure 1.

In cross-country health analyses, missing observations are often imputed to preserve geographic coverage and reduce bias from excluding countries with incomplete data (Little and Rubin 2020). Therefore, for the counterfactual analysis the missing entries in the dataset were replaced with imputed values using region-income averages. For this, countries were grouped according to the six WHO regional offices (WHO n.d.) and three World Bank income levels: high-, middle- and low-income (HI, MI and LI, respectively) (World Bank 2022), resulting in 18 region-income groups. Group sizes were calculated for each year, as some countries' income level changed over the years.

For the RTF_4W variable, missing country-level values were replaced by the means of the corresponding region-income group. In cases where a region-income group contained no available observations (e.g., single-country groups without reported data), values were imputed using the mean from the closest income group from the same geographic region. Seat belt wear rate data, however, were very scarce (especially in GSRRS 2023) and had too many empty region-income groups for this approach to work standalone (the data were reported by less than 50% of countries for all seating positions through all study years, as presented in Figure 1). Number of countries that have presented data for seat belt wear rate at least once in the three GSRRS releases were 110, 102 and 87 for drivers, front and rear occupants respectively.

A two-stage imputation procedure was applied to handle missing seat belt wear rate data. For each reporting year, missing country values were temporarily supplemented using seat belt wear rates reported by the same country in other GSRRS releases (if present); if values were reported in both other years, their mean was used. This cross-wave country information was used only to stabilize group-level estimates and was not retained as country-specific imputed values. Following this augmentation, region-income group means were computed for the year with fewer groups remaining empty. These group averages were used as the final imputed values for all countries with missing data for that year.

Legislative group classification

Countries were classified according to the scope of mandatory seat belt usage legislation, based on four GSRRS indicators: (1) validated existence of a general seat belt use law and requirements for (2) drivers, (3) front-seat occupants, and (4) rear-seat occupants. For each country-year, legislation was considered comprehensive only when all four indicators were reported as "Yes".

Because participation in GSRRS was incomplete across study years (173, 171, and 167 countries in 2013, 2018, and 2023, respectively), missing legislation data were addressed using temporal consistency rules. When a country did not participate in a given year but reported legislation status in an adjacent wave, values were carried backwards or forward where logically justified. In particular, when a country reported the absence of seat belt legislation in a later year, the same status was assumed for earlier nonparticipating years. Inherently, when a country reported the presence of legislation in an earlier year, this status was carried forward to subsequent nonparticipating years unless contradictory evidence was available. In selected cases, the earlier GSRRS 2009 release was consulted to verify legislative status (WHO 2009).

Based on the harmonized legislation data, countries were assigned to three mutually exclusive groups:

- Group 2.1 ($N=90$): countries with comprehensive seat belt usage legislation covering all occupants throughout the study period (2011–2021);
- Group 2.2 ($N=26$): countries that had not achieved comprehensive legislation in earlier years but were classified as comprehensive by 2021;
- Group 2.3 ($N=67$): countries not confirmed to have comprehensive legislation by 2021, including those with partial legislation coverage, missing 2021 data, or no participation during the study period. There was one country with no available GSRRS participation in any study year which was also assigned to this group.

Temporal interpolation of annual parameters

To quantify the excess vehicle occupant RTFs over the study period, gradual changes were assumed between the study years, and linear interpolation was applied to a set of variables that were used in a counterfactual analysis to estimate preventable RTFs (Bhalla and Gleason 2020; Antona-Makoshi et al. 2023). Interpolated variables for periods 2012–2015 and 2017–2020 were population, RTFs of the population, RFR_4W, Average belted 4 W occupant (AVG_SBR), and target AVG_SBR).

Counterfactual modeling framework

Globally preventable RTFs were quantified in two hypothetical scenarios. In the first scenario, countries without comprehensive seat belt legislation or those that achieved it only recently (i.e., groups 2.2 and 2.3) were assigned the seat belt wear rates observed in group 2.1 countries in each study year. For each year, countries whose observed average belted 4W occupant percentage exceeded the target value derived from group 2.1 countries were omitted from analysis, and eligibility was reassessed annually. The population of these countries will be described as "affected population".

For eligible countries, the preventable RTFs in a year were estimated as:

$$pRTF = RFR_4W * Pop / 100{,}000 * \left(AVG_SBR_{target} - AVG_SBR_{country} \right) * SB_{effect} \quad (1)$$

where RFR_4W is the 4W occupant road fatality rate per 100,000 population, Pop is the country population, AVG_SBR_{target} is target average belted 4W occupant percentage derived from group 1 countries, $AVG_SBR_{country}$ is the country-specific average belted 4W occupant percentage, and SB_{effect} is fatality risk reduction associated with seat belt use compared with nonuse. The formulation estimates baseline 4W occupant fatalities and applies the increase in seat belt use relative to the target level, scaled by the assumed effectiveness of seat belts. Based on literature, SB_{effect} was set to 50% (Crandall et al. 2001; Zhu et al. 2007).

A second scenario representing ideal global seat belt use was also evaluated. In this case, Equation (1) was applied with AVG_SBR_{target} = 100%, and all countries (i.e., Groups 2.1, 2.2 and 2.3) were included in this analysis, as none reported universal seat belt use across vehicle occupants.

Sensitivity analysis

Several constants and imputation methods were varied to assess their influence on the averted death estimation. They are presented in Table 2 and include seat belt effectiveness when used, usage target, and vehicle occupancy. Two occupant distributions are analyzed: (1) the "default" 70/20/10% distribution for drivers, front and rear occupants (described earlier), and amounting to an average occupancy of 1.43 person per trip, which is within the values reported in the literature (European Commission and Eurostat 2021); (2) a distribution with higher occupancy, resulting in an average occupancy of 3 people per trip (i.e., 33.3/33.3/33.3). Only corner and center states are calculated, resulting in a total of 10 scenarios of globally preventable RTFs for vehicle occupants' calculation where the target seat belt wear rate is derived from Group 2.1 wear rates. Saved life estimation when universal seat belt use is implied (100%) is performed in a total of 6 scenarios, utilizing both occupancy distributions and the three seat belt use effectiveness of fatality reduction.

Table 2. Sensitivity analysis matrix.

Occupancy distribution (driver/front/rear), %	70/20/10			33.3/33.3/33.3		
Seat belt fatality reduction effectiveness, %	35	50	65	35	50	65
Average seat belt use rate target: Group 2.1 – median, %	69.4*	–	69.4	59.0	–	59.0
Average seat belt use rate target: Group 2.1 – mean, %	–	69.8	–	–	62.2	–
Average seat belt use rate target: Group 2.1–75th percentile, %	83.9	–	83.9	77.4	–	77.4

*The median, mean and 75th percentile values of target seat belt use are presented as averages of the 2011–2021 period.

Results

Descriptive analysis

The 183 countries comprised 6308.9, 6731.4 and 7236.1 million people in 2011, 2016 and 2021, respectively (Table 3). These represent 90.1-91.4% of the world population (all ages) depending on year. In 2021, 109 countries required seat belts installed in all seating positions, covering, in principle, about 80% of the global population, while 32 countries limited the requirement to front seats, 10 reported no such legislation, and 25 abstained from reporting the information. For at least 3% of the population, seat belt presence is entirely optional. No data are available on national vehicle fleet composition or age, which may lead to an overestimation of effective coverage, as some vehicles may be exempt from seat belt requirements.

By 2021, fewer than half of countries had national laws on seat belt or anchorage standardization, although these countries accounted for 61-74% of the global population. However, in many of these countries the referenced standards do not necessarily reflect internationally recognized best practices, affecting 50-57% of the global population. 17% of global population benefits from national seat belt standardization laws that align with UNECE regulations, and 12% from anchorage standardization laws that similarly adhere to those regulations.

Countries whose legal equipment standards adhere to UNECE regulations (N=32 for seat belts; N=29 for anchorages) had the lowest observed average RFR_4W, at 3.2 and 2.6 deaths per 100,000 population, respectively. Countries implementing UNECE-compliant standards without national laws showed similar fatality rates (4.7 and 4.8), while those with national laws not aligned with UNECE standards had slightly higher rates (4.7 and 5.3). The highest average RFR_4Ws were observed in countries lacking both national standardization laws and adherence to UNECE regulations.

Table 3. Distribution of 183 countries and their joint population by income level and year.

Income group	Year	Population (million.)	No. of countries
Low	2011	691.1	36
	2016	570.0	32
	2021	616.6	28
Middle	2011	4591.4	100
	2016	5075.7	101
	2021	5471.5	102
High	2011	1026.4	47
	2016	1085.7	50
	2021	1148.0	53

The prevalence of mandatory seat belt use laws across the 183 countries and the corresponding population covered by such laws are shown in Figure 2. Results are shown for overall seat belt legislation and by seating position: drivers, front-seat occupants and rear-seat occupants. Population coverage exceeds the share of countries with legislation, indicating that countries without such laws tend to be less populous. Since 2011, the largest increase in population coverage was seen for front-seat occupants – an increase of 26%. Both general seat belt legislation and its applicability to drivers rose by 12% globally. Its applicability to rear-seat occupants was the lowest in 2011 and saw the smallest increase in population coverage (10%). In 2021, over 98% of the population was covered by seat belt laws for drivers, yet more than 35% of countries and one quarter of the global population lacked a rear-seat requirement.

Variation of the legislation over the years by country income group is shown in Table 4, where it is assessed for both countries and population of the income groups. The largest increases were observed in coverage for front-seat occupants (19-54% increases of covered population since 2011). LICs have the fewest mandatory seat belt wear laws, while HICs have the most. Front- and rear-seat occupant coverage levels were relatively similar in 2011, but the gap widened by 2021 globally, particularly in LICs. Between 2011 and 2016, front-seat legislation increased across all income groups, with LICs showing the most pronounced improvements. Still, 6% and 13% of middle- and low-income countries' populations remained uncovered by these laws, respectively. These percentages increase when legislation is examined by seating position, up to 50% of LICs population living in countries that do not have legislation including rear seat occupants.

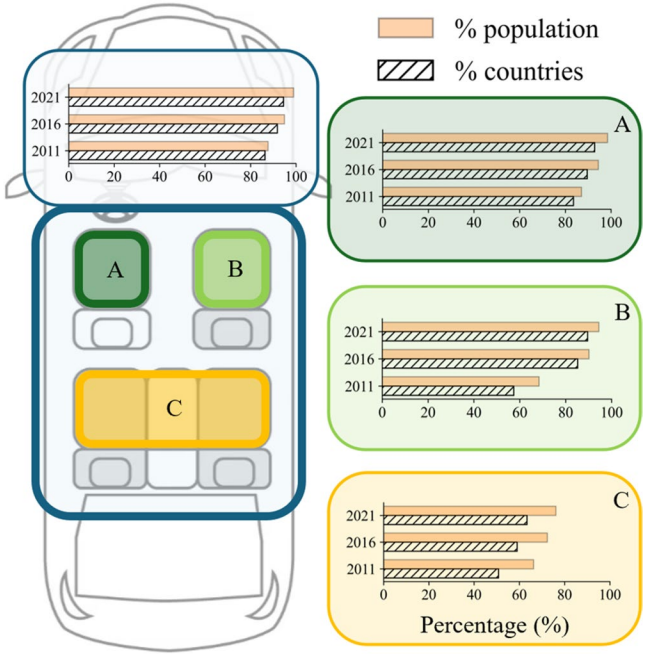

Figure 2. Mandatory seat belt use laws: Presence and population coverage by year and seating position.

In addition to legislative scope, differences were observed in national reporting of vehicle occupancy or seat belt use data. Table 4 presents reporting patterns across GSRRS releases by country income group, assessed for both countries and population of the income groups. LICs provide the least information on road fatality user distribution and seat belt wear rates across all study years, whereas HICs consistently showed the highest reporting levels. Availability of data increased among LICs over time, particularly for RTF_4W data, which rose by more than 15% since 2011. Nevertheless, the proportion of populations without monitoring remains 32%, 6%, and 4% for LICs, MICs, and HICs, respectively.

Reporting of seat belt wear rates declined significantly in middle- and high-income countries, with the number of countries in 2021 decreasing by 22-38% compared to 2016 (Table 5). In 2021, the proportion of the population living in countries that did not report seat belt use ranged from 27% in HICs to 95% in LICs.

Whether differences in reporting were accompanied by differences in estimated mortality levels is shown in (Figure 3). In the plot, marker size reflects the proportion of countries within each group reporting the RTF_4W data in the respective year. Group 1.1 ($N=10$) has reported the data for all occupants in all three years, Group 1.2 ($N=108$) has provided the data at least once for any occupant, and Group 1.3 countries ($N=65$) have not reported seat belt wear rates. Group 1.1 shows both the lowest average RFR_4W and largest relative decrease in the rate by 2021. The average RFR_4W for Group 1.1 is over three times smaller than for Group 1.3; the latter also was the only group to see an increase of RFR_4W between the 10 years, while the other two groups showed reductions of over 30%. Because no data was imputed at this stage, the average RFR_4W values for Group 1.3 represent only 43-62% of countries depending on the year.

Table 4. Percentage of countries and joint population covered by mandatory seat belt use legislation (general and occupant-applicable) by income level and year.

Income group	Year	Percentage of countries with mandatory seat belt use laws, %				Percentage of population, covered by mandatory seat belt use laws, %			
			Applicable to:				Applicable to:		
		General	Driver	Front Occ	Rear Occ	General	Driver	Front Occ	Rear Occ
Low	2011	63.9	58.3	33.3	25	60.4	57.8	33.6	28.4
	2016	78.1	75	71.9	31.2	86.3	83.6	79.0	38.2
	2021	85.7	82.1	82.1	42.9	90.0	87.1	87.1	49.9
Middle	2011	90	87	56	48	95.4	95.0	73.3	71.2
	2016	93.1	90.1	85.1	54.5	94.8	94.5	89.4	76.5
	2021	95.1	93.1	88.2	56.9	99.8	99.5	94.1	80.1
High	2011	95.7	95.7	78.7	76.6	71.7	71.7	69.7	69.6
	2016	98	98	94	86	100.0	100.0	99.8	71.0
	2021	98.1	98.1	96.2	86.8	100.0	100.0	100.0	71.1

Additional components of the seat belt legal framework – including penalty systems for noncompliance, and applicability exceptions – were also associated with differences in RFR_4W. In both 2016 and 2021, countries with a penalty system ($N=148$; 151, respectively) tended to report lower RFR_4W than those without ($N=35$; 32). In 2016, the average RFR_4W difference between the groups was 1.2 deaths per 100,000 population (+22%); for 2021, the difference increased to 1.4 deaths per 100,000 (+30%). In 2021, more than half of countries worldwide had some form of exemption to mandatory seat belt use laws, which in turn affected almost one-fourth of global population. The most prevalent applicability was for medical reasons (40% of countries; 16% of population), followed by exceptions for taxi drivers (18%; 8%), pregnant women (9%; 7%), and government officials (3%; 2%). Within the countries that had comprehensible seat belt laws by 2021 ($N=116$), the exceptions were more likely in high-income countries. Only 17% of countries that had no exceptions to their seat belt use laws, consisted of HICs.

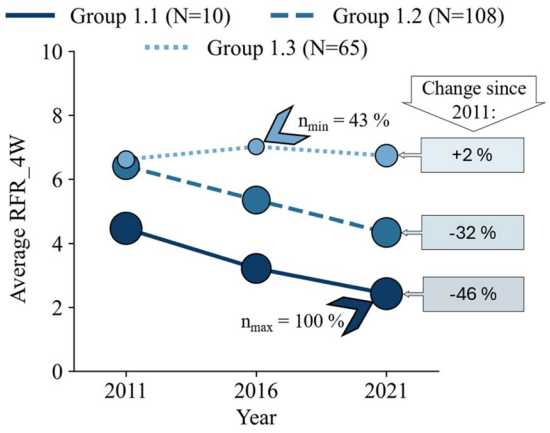

Figure 3. Average four-wheeler road fatality rate 100,000 population by seat belt wear–rate reporting group and year.

Counterfactual and sensitivity analyses

Over the period of 2011–2021, between 1.14 and 1.2 million people were estimated to die each year due to RTIs, resulting in over 12.8 million fatalities over 11 years (3.2–3.9 million being 4 W occupants). Over 31% of these fatalities were recorded in countries that did not have a comprehensive set of mandatory seat belt use laws (Group 2.3) or implemented them only recently (Group 2.2) and reported lower seat belt wear rates than countries that have the comprehensive legislation (not characterized as "omitted" in a specific year). Should vehicle occupants in these countries have worn seat belts at the same rate as Group 2.1 occupants had on average, 7,500-9,800 deaths per year (almost 100,000 over the study period) could have been prevented. This represents 2.4% of fatalities of the affected population, and 0.8% of global RTFs over 11 years.

If 100% of all vehicle occupants over the 183 countries had worn seat belts over 2011–2021, 60,000 to 86,000 lives would have been saved every year. This amounts to almost 800,000 4 W occupant fatalities that could have been averted over 11 years, corresponding to 6.2% of the global RTI fatality burden (Tables 6 and 7).

Sensitivity analyses showed that preventable deaths ranged from 65,000 to 239,500 under the default 70/20/10 occupancy distribution (Table 6). This corresponds to 1.7-5.3% of

Table 5. Percentage of countries and joint population that have provided data related to vehicle occupancy monitoring by income level and year.

		Percentage of countries reporting occupancy data, %				Percentage of population, living in countries that report occupancy data, %			
		Reported RTF_4W,	Reported SB wear rates:			Reported RTF_4W,	Reported SB wear rates:		
Income group	Year	%	Driver	Front Occ	Rear Occ	%	Driver	Front Occ	Rear Occ
Low	2011	36.1	5.6	2.8	0	52.7	13.6	2.7	0
	2016	37.5	9.4	6.2	0	54.4	5.6	3	0
	2021	53.6	14.3	7.1	7.1	68.2	6.7	5.3	16.1
Middle	2011	69	42	38	25	86.2	49.6	16.5	8.7
	2016	68.3	41.6	39.6	31.7	58	68.2	43.4	16.8
	2021	79.4	19.6	14.7	8.8	93.6	14.5	12.2	6.3
High	2011	87.2	70.2	66	70.2	97.4	88.2	84	90.1
	2016	88	62	68	64	92.5	80.7	93.6	93
	2021	92.5	37.7	30.2	26.4	95.5	72.7	70.3	32.8

Table 6. Excess 2011–2021 road traffic fatalities by seat belt effectiveness, target seat belt wear rate and occupancy distribution.

	Total number, N			Percentage of fatalities of the affected* population, %			Percentage of fatalities of the global population, %		
Group 2.1 (target) SB wear rate	SB effectiveness, %								
	35	50	65	35	50	65	35	50	65
	Occupancy distribution: 70/20/10%								
Median	65,082	–	120,867	1.7	–	3.1	0.5	–	0.9
Mean	–	95,851	–	–	2.4	–	–	0.8	–
75th percentile	134,597		239,473	3.0		5.3	1.1		1.9
	Occupancy distribution: 33.3/33.3/33.3%								
Median	41,558	–	77,179	1.3	–	2.4	0.3	–	0.6
Mean	–	78,475	–	–	2.1	–	–	0.6	–
75th percentile	126,693	–	235,288	2.9	–	5.5	1.0	–	1.8

*Affected means population of groups 2.2 and 2.3 countries minus those with reported seat belt usage equal or higher than average of group 2.1 countries.

Table 7. Excess 2011–2021 road traffic fatalities with 100% target seat belt use by seat belt effectiveness, and occupancy distribution.

Occupancy distribution, %	SB effectiveness, %		
	35	50	65
	Life saved, N		
70/20/10	556,894	795,563	1,034,232
33.3/33.3/33.3	613,313	876,161	1,139,010
	Life saved, %*		
70/20/10	4.3	6.2	8.1
33.3/33.3/33.3	4.8	6.8	8.9

*Was calculated as a proportion of life saved [N] and global population sum over 2011–2021.

fatalities in the affected population, or 0.5-1.9% of global fatalities. In the "universal seat belt use" scenarios with this occupancy distribution, 557,000–1,034,000 deaths could have been prevented (4.3-8.1% of global RTFs in 2011–2021) (Table 7).

For the scenario with three occupants in each vehicle, using otherwise "default" values of seat belt effectiveness and Group 2.1 seat belt wear rate as a mean, 78,500 lives would have been saved over the study period, which corresponds to 2.1% of the affected population fatalities, or to 0.6% of global RTFs. With the implementation of sensitivity analysis, intervals of 41,500-235,000, 1.3-5.5% and 0.3-1.8% respectively were obtained. Numbers of averted fatalities in the "universal seat belt use" scenarios were larger with this occupancy distribution – between 613,000 and 1,139,000, equivalent to 4.8-8.9% of global population RTFs over the 11 years.

Discussion

The effectiveness of seat belts in reducing fatal injury risk has been consistently demonstrated across experimental and epidemiological studies (Bohlin 1967; Abbas et al. 2011). Yet the population-level benefit of this intervention depends on the integrity of its implementation (Bachani et al. 2017). Vehicles must be equipped with seat belts; equipment should meet standards; usage should be encouraged; if mandates are imposed, enforcement must be established; information systems to monitor all these steps must exist to assess effectiveness and guide policy adjustments. This multi-layered implementation framework has been well described in road safety literature (FIA Foundation 2022). The persistence of gaps in equipment regulation, legislative scope, and monitoring capacity suggests that the life-saving potential of seat belts remains incompletely realized in many settings.

Nearly 60 years after Bohlin's 1967 publication and subsequent evidence confirming the safety benefits of seat belts, and international policy commitments, 74 countries – representing one-fifth of the global population – did not legally require their presence in all vehicle seats as of 2021. Whether such legal requirements exist for any seating positions remains unknown for several countries, representing additional 8% of the global population. Fewer than one-third of countries had adhered to the 1958 Agreement (United Nations 2017), limiting the global adoption of harmonized technical standards for seat belt systems and anchorages. While delayed adoption of safety technologies across countries is consistent with broader patterns of technological diffusion, particularly in low- and middle-income settings (Comin and Mestieri 2018), these findings indicate that, even before individual compliance is considered, institutional frameworks in many settings do not consistently ensure that proper restraint systems are available to all 4Ws.

Voluntary seat belt use rates are low, and legal requirements with enforcement are the most effective strategy to increase it (Abbas et al. 2011). As of 2021, 67 countries, comprising 24% of the population, have failed to adopt state-of-the-art legislation on the matter. Furthermore, 28 other countries (representing another 12% of the population) have only improved this situation starting in 2011, nearly 50 years after Bohlin's work. The delayed adoption of comprehensive seat belt legislation suggests that large populations may have remained exposed to elevated risk for decades despite the long-standing availability of an effective intervention, highlighting the potential prevention gap estimated in this analysis.

Another indication of this limited institutional attention is the weak development of national systems for monitoring 4W occupant safety. Ninety-nine Member States, representing 55% of the population, have reported the user distribution of road traffic fatalities consistently across the study years. Monitoring of seat belt use is considerably more limited: only 10 countries (accounting for 4% of the population) have consistently reported these data regarding all vehicle occupants. Moreover, the number of countries reporting seat belt wear data declined significantly by 2021. While this decline may partly reflect temporary disruptions in data collection or reporting processes, the consistently low levels of monitoring observed across all study years indicate that monitoring capacity remains fragile and inconsistently enforced across countries.

The counterfactual analysis indicates that the unrealized safety benefit of seat belt use remains measurable even under conservative assumptions. Using wear rates already observed in countries that had more mature seat belt use legislation as the benchmark, around 96,000 4W occupant deaths between 2011 and 2021 could have been prevented globally, assuming 50% seat belt effectiveness and the baseline 70/20/10 occupancy distribution. Although this corresponds to less than 1% of all global road traffic fatalities, it represents about 2-3% of deaths among populations where seat belt adoption remains incomplete or very recent, indicating that relatively modest improvements in compliance are consistent with meaningful reductions in occupant mortality. At the opposite end of the sensitivity spectrum, the most optimistic scenario – assuming universal seat belt use throughout the study period – suggests that over one million occupant deaths worldwide may have been prevented during the study period. These findings highlight that even in countries with comprehensive seat belt legislation in place by 2011, wear rates averaged below 80% for front occupants and below 50% for rear occupants, thus highlighting persistent gaps between legislative adoption and behavioral compliance.

Other modeling studies evaluating the mortality impact of seat belt interventions have generally examined scenarios of large-scale or full implementation of multiple safety measures.

For example, increased seat belt use in Latin America and the Caribbean was estimated to reduce road traffic deaths by 12% in the region (Bhalla and Gleason 2020), while in the Association of Southeast Asian Nations region, universal seat belt adherence would reduce regional deaths by 11% (Antona-Makoshi et al. 2023). At the global level, seat belt interventions were estimated to prevent approximately 121,000 deaths annually worldwide (Vecino-Ortiz et al. 2022). These studies therefore evaluate the potential effects of interventions under best-case implementation scenarios. In contrast, the present analysis addresses a narrower policy question: vehicle occupant mortality associated with delayed or incomplete adoption of comprehensive seat belt legislation. Rather than assuming universal seat belt use, seat belt wear rates in countries without long-standing comprehensive legislation were aligned to levels already observed in countries with more mature legislative and monitoring frameworks. Consequently, the estimates reported in the most conservative scenario in this study are smaller, reflecting a counterfactual based on realistic policy performance rather than the aspired universal intervention adoption.

Several limitations of the excess mortality estimation modeling should be acknowledged. First, important data gaps persist regarding vehicle fleet age and composition and national data on vehicle occupancy and seat belt use. The counterfactual analysis therefore assumed that vehicles circulating in national fleets were equipped with seat belts in all seating positions, although legal requirements for rear-seat belt installation are not universal. Missing observations for seat belt use and occupancy were addressed using regional and income-group averages, which may mask country-specific conditions. Rear-seat wear rates also were reported scarcely through the study years, and thus most affected by the imputation process; although their influence on the estimates is limited by the lower weight assigned to rear occupants in the assumed seating distribution. As a robustness check, the Multiple Imputation by Chained Equations (MICE) method was used as an alternative missing data treatment, and the counterfactual analysis was repeated. Region-income grouping and seat belt legislation indicators were used as predictors. The method yielded similar estimates of deaths averted over 11 years, with differences of <0.3%, suggesting that the main findings are not sensitive to the choice of imputation method.

Seat belt use data are generally obtained through dedicated monitoring activities, such as surveys, roadside observations, surveillance systems, or camera-based detection (Hasan et al. 2025). Because these approaches require sustained national monitoring efforts, inconsistent reporting across GSRRS waves may reflect the absence of regular data collection programs rather than changes in actual seat belt use. In the counterfactual modeling, uniform seat belt effectiveness was applied across countries, also introducing limitations. While seat belt systems themselves are not expected to perform differently across countries, their observed effectiveness may vary depending on factors such as the presence of other vehicle safety systems (e.g., airbags), vehicle fleet composition, and crash characteristics. A fixed seating distribution was also assumed based on values reported in the literature, although most occupancy studies originate from HICs and comparable data for low- and middle-income settings remain limited. Finally, population and road traffic fatality figures from the Global Health Estimates are themselves modeled values whose reliability depends on the quality of national surveillance systems.

Future work could extend this framework by examining the reliability of reported data and introducing weighting approaches that reflect differences in monitoring capacity, development level, and data completeness across countries. Such analyses could explore alternative modeling scenarios where legislative scope, enforcement strength, and monitoring quality are considered together, providing a clearer picture of how national conditions influence preventable vehicle occupant mortality.

Conclusions

In 2010, United Nations Member States unanimously adopted Resolution 64/255 and committed to halving road traffic fatalities through the 2011–2020 Decade of Action for Road Safety. Over the following decade, global road traffic mortality declined by 5% (WHO 2023). The extent to which this decline was related to improvements on seat belt usage was not assessed. However, the counterfactual analyses presented in this study are consistent with additional reductions of 1-8% under improved seat belt use scenarios. Unquestionably, more improvement would have been observed had safety belt equipment and legislation been better adopted. Many more lives could have been saved prior to 2011, too.

More than fifty years after the introduction of the three-point seat belt, important gaps persist in the global framework required to fully benefit from this intervention. Many countries still lack comprehensive legislation requiring seat belt availability and use for all occupants, equipment standards, and national monitoring systems for seat belt use remain limited. These gaps indicate that the life-saving potential of one of the most effective road safety interventions has not yet been fully realized. Additional interventions could also be developed and/or more widely implemented, ranging from restricting the registration of seats without seat belts (Gobierno de Uruguay 2010), to improving restraint system designs to better accommodate occupants of different body sizes and characteristics (Boyle et al. 2020). However, significant progress could still be achieved simply by implementing the legislative, technical, and monitoring measures that already exist – there are still opportunities to advance toward the universally adopted targets of UN GA 74/299 (United Nations General Assembly 2020) and other related goals.

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Author contributions

CRediT: **Ema Jokūbaitytė**: Conceptualization, Formal analysis, Methodology, Software, Validation, Visualization, Writing – original

draft, Writing – review & editing; **Gonzalo Casas**: Conceptualization, Writing – review & editing; **María Seguí-Gómez**: Conceptualization, Data curation, Methodology, Supervision, Writing – original draft, Writing – review & editing.

Use of generative artificial intelligence

Artificial intelligence (AI) tools (ChatGPT, OpenAI) were used to assist with code development and to improve the clarity and grammar of English language in the manuscript. All scientific content, analysis, and interpretations were developed and verified by the authors.

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Data availability statement

Data from the Global Status Report on Road safety of 2013, 2018 and 2023 can be found here: Global Status Reports on Road Safety.

Data from the Global Health Estimates of 2010, 2015 and 2021 can be found here: Global Health Estimates: Leading Causes of Death by Country (Estimated deaths ('000) by age, cause and sex).

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