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Research Article

Toward zero traffic deaths and disabilities with active and passive safety technologies in the association of southeast Asian nations

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A B S T R A C T

Road traffic crashes caused more than 108,000 deaths and 6,200,000 injuries resulting in 7.7 million disability-adjusted life years (DALYs) lost in the Association of Southeast Asian Nations (ASEAN) in 2019. This study estimates that 59 % of these casualties could have been avoided if all vehicles were designed to provide crash protection equivalent to that of the best vehicle safety design in their class and all road users adhered to safety best practices. Results of comparative risk assessments indicate that the application of safety technologies that are considered high priority by the United Nations (anti-lock braking, electronic stability control, occupant restraints, frontal and side airbags, crashworthiness, side-door beam, side structure and padding, and helmets) can save 34,373 lives and avert 2.5 million DALYs annually in ASEAN. While implementing Autonomous emergency braking and lane keeping assistance systems would provide additional reductions estimated at 13,077 fewer deaths and 1,021,220 fewer DALYs, speed-limitation systems would have a larger additional benefit, estimated at 21,394 lives saved and 1,382,530 fewer DALYs. The investigated technologies can be among the best approaches toward zero traffic deaths and can elevate public health burdens in low and middle-income countries.

1. Introduction

In 2021, the Global Plan for the Decade of Action for Road Safety (2021−2030) targeted preventing 50 % of road traffic deaths and injuries by 2030 [1]. Yet, road traffic death rates vary substantially among countries. Statistics from the World Health Organization (WHO) show that 79 countries, mostly high-income, have done well at reducing traffic death rates over the last few decades. In contrast, traffic death rates in 68 countries, mostly low and middle-income, have increased or remained high [1]. Understanding what was effective in countries with low death rates and what is exclusive to countries with high death rates is critical for achieving this global target.

1.1. Study motivations

The United Nations (UN) World Forum for the Harmonization of Vehicle Regulations has established a legal framework and prioritized eight vehicle design-related regulations (1958 and 1998 UN conventions). These include anti-lock braking systems (ABS), electronic stability control (ESC), occupant restraints (seatbelts and child seats), frontal and side airbags, side door beams, side structure and padding, and vehicle front-end design for pedestrian protection (crashworthiness). Studies from the USA concluded that light vehicle design improvements between 1960 and 2012 have had a significant impact on reducing traffic deaths for vehicle occupants in the country compared to all other road risk factors combined [2,3]. For example, motorcycle ABS reduces the risk of death in motorcyclists by 31 % [4,5]. Several studies reported that ESC can reduce crashes caused by skidding and loss of control in passenger vehicles by more than 41 % [6–9]. Crashworthiness or front-end vehicle design to reduce the impact of a collision with Vulnerable Road Users (VRUs) has proved effective in protecting pedestrians, bicyclists, and users with reduced mobility [10,11]. Besides continual improvements in car occupant protection, interventions to protect VRUs, such as helmets, have been gaining momentum in high-income countries (HICs). A Cochrane review demonstrated that motorcycle helmets reduce the risk of death and non-fatal head injuries in motorcyclists who crashed, respectively, by 42 % and 69 % [12]. The real-world effects of vehicle safety technologies and protective devices are well established [13,14]. However, the implementation of these priority UN regulations is limited to only 40 countries, mainly high-

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income, while 124 low and middle-income countries (LMICs) require only one (or none) of the regulations [15]. As a result, these fundamental safety interventions are less accessible in in-use and new vehicles sold in LMICs compared to HICs.

With a combined population of over 660 million, the Association of Southeast Asian Nations (ASEAN) is a fast-growing economic bloc comprised of 10 member states: Brunei Darussalam, Cambodia, Indonesia, Lao People's Democratic Republic, Malaysia, Myanmar, Philippines, Singapore, Thailand, and Viet Nam. In 2019, the region boasted a significant automobile industry with approximately 63 million passenger cars and 221 million motorcycles [16]. Such growth in the automobile sector is associated with a large number of road traffic deaths, totaling 108,000 fatalities in 2019 [17]. Most ASEAN countries have not ratified the 1958 and 1998 UN conventions related to wheeled vehicle equipment and parts, which are among the eight most relevant road safety-related UN conventions for road safety. The exceptions are Malaysia, which adheres to both conventions, and Thailand, which adheres to the 1958 convention. The importance of these conventions and regulations is emphasized in UN road safety (voluntary) performance target 5, which aims to ensure that by 2030, "100% of new (produced, sold, or imported) and used vehicles meet high-quality safety standards, such as the priority UN Regulations, Global Technical Regulations, or equivalent recognized national performance requirements" [1]. This study sought to investigate the impact of adhering to vehicle safety standards and safety best practices on road traffic deaths and injuries in the ASEAN region.

1.2. Background

A significant disparity exists between the safety performance of vehicles produced and sold in LMICs compared to those sold in HICs [18]. Bhalla and Gleason (2020) investigated the effects of implementing the priority eight UN regulations in reducing traffic deaths and disability-adjusted life years (DALYs) lost in Latin American and Caribbean countries [19]. They found that ESC, including ABS, would have the largest benefit in reducing deaths and injuries while increasing the use of seatbelts and improving side and frontal vehicle design would prevent further fatal injuries. A follow-up study applied a similar strategy to model improvements in vehicle design and other well-known effective interventions, such as helmets, speed control, drunk driving policies, and crashworthiness, in six LMICs: China, Colombia, Ethiopia, India, Iran, and Russia [20]. The study concluded that speed control and crashworthiness have the highest potential to save lives. Another study conducted a cost-benefit analysis of the ESC impact in the G20 countries, including Indonesia, and concluded that ESC could save 42,000 lives in these countries, with the cost of such technology being small compared with the benefits [21]. A comprehensive study that estimated the reduction in road deaths and injuries by the application of a set of vehicle safety regulations until 2030 in Brazil, Argentina, Chile, and Mexico indicated that the combined set of technologies, including ESC and crashworthiness, would become cost beneficial latest by 2026 [22]. A more recent study has established that between 25 % and 40 % of all fatal road injuries worldwide can be averted by addressing four road risk factors: speeding, drunk driving, helmet use, and the use of seatbelts and child restraints [23]. These risk factors contribute to the high road traffic death rates observed in LMICs, including the ASEAN region, where motorcycle crashes remain a predominant concern.

In addition to vehicle safety design, advanced driver assistance systems (ADAS) safety features that have long been mass-produced in the new vehicle fleet play a significant role in improving driving performance and reducing road traffic crashes in HICs. Empirical studies, field tests, and real-world data have shown that collision avoidance systems, such as forward collision warning (FCW), autonomous emergency braking systems (AEBS), lane departure warning/prevention (LDW/P), lane keeping and centering systems (LKA), provide substantial protection for car occupants and VRUs [20,24–27]. For example, an investigation that compared low-speed AEBS versus no-AEBS cars based on insurance claims data estimated that 27 % of rear-end frontal collisions were reduced with a 37 % reduction of low-severity crashes and 47 % reduction of occupant injuries in vehicles struck by low-speed AEBS cars [28]. Further, filed tests of some ADAS features concluded that AEBS can reduce rear-end striking crashes by 46 % [27].

Jermakian (2011) estimated that LDW/P systems could prevent up to 179,000 crashes, including 7500 fatal crashes, every year in the United States [29]. Sternlund et al. (2017) compared similar vehicles with and without lateral safety systems in Sweden and estimated that such systems reduce head-on and single-vehicle injury crashes by 53 % on roads with speed limits between 70 and 120 km/h [30]. Cicchino (2018) found that LDW-equipped vehicles had an 11 % lower rate of involvement in single-vehicle, sideswipe, and head-on crashes compared to the same vehicles with no LDW systems; for crashes with injuries, the LDW system reduced crash involvement by 21 % after controlling for driver demographics [31]. Therefore, implementing such ADAS safety features in vehicles that comply with the UN Conventions 1958 and 1998 can boost safety and provide an additional reduction in deaths and injuries.

Furthermore, the crash probability increases as driving speed increases, and so does road user vulnerability with the highest influence being on vehicle-to-VRU crashes [32]. An increase in speed of just 1 km/h leads to a 3 % increase in the risk of a crash involving injury, with the risk escalating exponentially as speeds rise [33]. Moreover, it is estimated that speeding contributes to approximately 30 % of all road traffic fatalities in HICs and up to 50 % in LMICs [34]. A meta-analysis has indicated that a 1 % increase in average speed results in a 4 % increase in fatal crashes [35]. Note that the effectiveness of vehicle safety interventions and user protective devices varies greatly with different crash speeds. Although active and passive safety systems can provide significant protection for their users at any speed range when compared to non-users, their protection decreases as the crash speed increases [36]. For example, a more recent AEBS may avoid collisions entirely at speed ranges less than 60 km/h, while the system becomes less effective at a higher speed range. The literature highlights the critical role of speed management strategies in reducing the incidence and severity of road traffic crashes, emphasizing the importance of interventions such as speed limitation measures. Therefore, this study includes the safety benefit of speed limitation systems, which aim at encouraging drivers to be more compliant with speed limits, and hence reduce the likelihood of traffic conflicts caused by inappropriate speed [20]. There are different speed limitation devices, such as haptic feedback, speed control, acoustic, and vibrating systems; however, we will not discuss the effects of types of speed-limitation systems.

1.3. Aims

This study aims to investigate the benefits of implementing three groups of safety features: 1) the eight priority UN safety technologies, 2) road user protective devices, and 3) crash avoidance and speed limitation technologies in the ten ASEAN countries. Our analysis relies on the Comparative Risk Assessment (CRA) method which is commonly used to systematically evaluate the changes in population health resulting from a change in exposure to a risk factor. In this study, the risk factor is poor vehicle design and low rates of using protective devices. The counterfactual scenario is a vehicle fleet with safety technologies similar to those available in HICs (complying with UN safety conventions and fitment of safety-critical features of ADAS) and all road users adhering to safety best practices of using seatbelts, child restraints, and helmets. Finally, we quantified the decline in road traffic deaths and injuries that would ensue in ASEAN nations if their vehicle fleets achieved comparable levels to those observed in HICs. The current study adds value to our previous findings [37] by integrating a wider range of active and passive safety technologies, including collision avoidance systems.

2. Methods

2.1. Research approach and scope

Our research applies a CRA approach to evaluate the health burden attributable to a risk factor or group of risk factors, such as lack of safety measures or unsafe practices, and to estimate the proportional changes in deaths and injuries if the exposure to the risk factor was reduced to an alternative (counterfactual) scenario. Hereinafter, the risk factor is poor vehicle design and low rates of using protective devices. The counterfactual scenario is a vehicle fleet with safety technologies similar to those available in HICs and all road users adhering to safety best practices. We investigated the potential impacts of the following factors:

i) Improving vehicle safety design by implementing the eight vehicle design-related UN regulations: ABS, ESC, occupant restraints, frontal and side airbags, side door beams, side structure and padding, and crashworthiness.
ii) Promoting safety best practices of using protective devices: seatbelts, child restraint systems, bicycle helmets, and motorcycle helmets.
iii) Implementing three ADAS features: AEBS, LKA, and speed-limitation systems.

The flowchart in Fig. 1 presents the structure of our study and research process. The process incorporated four steps: 1) gathering information; 2) modeling the country-level burden of disease based on the annual deaths and injuries in 2019, and modeling the potential reduction in deaths, injuries, and DALYs by safety technology or group of technologies; 3) applying counterfactual analysis using CRA approach; and 4) conducting sensitivity analysis and producing results. The assessments involved several country-level evaluations incidence of traffic deaths and injuries categorized by road user type, sex, and age group to calculate the baseline DALYs as an indicator of the time lost by an individual due to living with a disability or premature death. We also estimated the prevalence of the related safety technologies and their use in each country. The relative risk of death and injury associated with each safety intervention under different crash configurations was estimated to calculate the reduction in deaths and DALYs if all vehicles had the intervention, or all road users used the intervention. However, our analysis contained information uncertainty and variations among multiple sources. To present the impact of information variations, we conducted a sensitivity analysis of the results based on alternative modeling assumptions and different sources.

2.2. Traffic deaths and injuries data

We estimated the baseline traffic deaths and injuries categories by road user type, age, and sex in each country considering three main sources: WHO's Global Health Estimates (GHE), the Global Burden of Disease (GBD) study, and national sources. The WHO's GHE provides information regarding the global causes of death and disability, sourced from various data sources, including the GBD study. The GBD study from the Institute of Health Metrics and Evaluation represents a comprehensive effort to measure epidemiological data worldwide.

Injury data is significantly less reported than death data, making it harder to obtain with fewer sources available for injury estimation and modeling. Consequently, we employed a combination of the three sources. We used GBD data for the total number of deaths and injuries, further disaggregating this data using road user type proportions reported in the WHO's GSRRS or, when available, more recent (2019) official statistics. When official statistics did not provide road user type proportions, we relied on the GBD death and injury proportions. However, our analysis accounts for this substantial uncertainty in the number of road traffic deaths and injuries through a sensitivity analysis of the estimates, as reflected in the wide 95 % confidence intervals from the GBD.

Fig. 2 shows the annual road traffic deaths and injuries per country in 2019, disaggregated by road user type (pedestrians, bicyclists, motorcyclists, occupants, and others). DALYs were calculated based on annual deaths and injuries using the burden calculator tool (online: http://calculator.globalburdenofinjuries.org) developed by Bhalla and Harrison (2016). It is apparent from the figures that the number of deaths and DALYs differ substantially among the ten countries, whereas the percentages of road user deaths and DALYs tend to be more akin. The data show that Indonesia, Viet Nam, and Thailand have the highest numbers of deaths and DALYs, and Brunei and Singapore have the lowest. However, in terms of death rate per 100, 000 population, Thailand (28.0) is the highest followed by Viet Nam (25.0) with Singapore (3.9) being the lowest. Such differences are attributed to several factors, such as population size and distribution, road infrastructure, traffic law enforcement, the dominant mode of road transportation (walking, cycling, motorcycle, rickshaw, cars, and buses), and the reporting rate of road traffic crashes in each country. For more

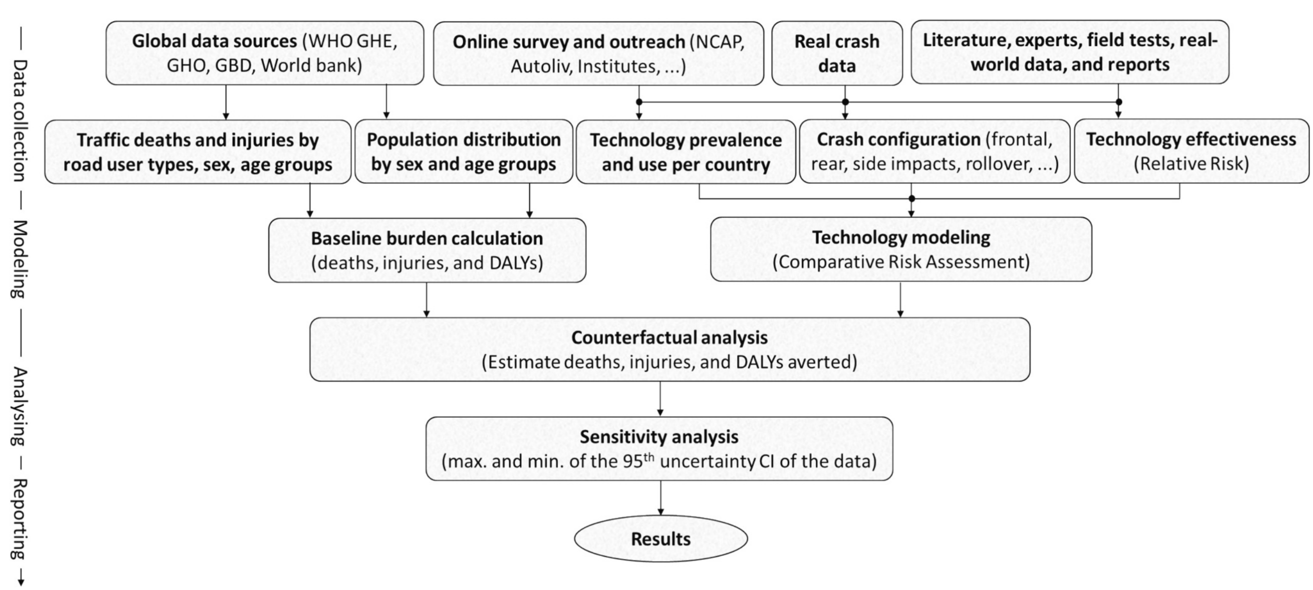

Fig. 1. Structure of the research process.

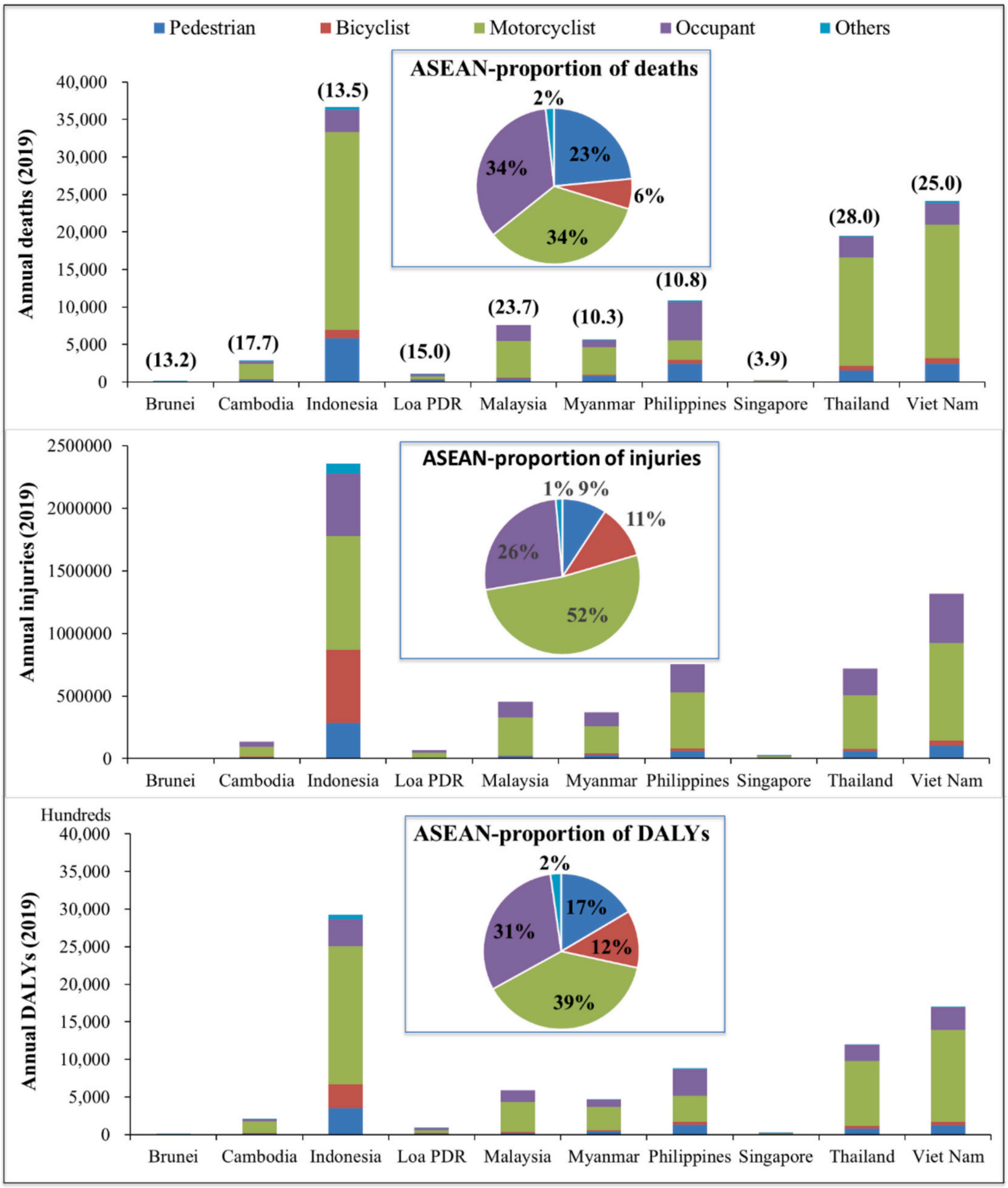

Fig. 2. The estimated annual road traffic deaths (top), injuries (middle), and DALYs (bottom) categorized by road user types in the ASEAN countries (2019). DALYs are calculated based on deaths and injuries data. Values in brackets represent road traffic deaths per 100,000 inhabitants in each country. Pie charts represent the proportions of each type of road user in the whole ASEAN region.

details, refer to Fig. A1 in the appendix.

2.3. Technology effectiveness, fitment rate, and use

We used the relative risk (RR) as an indicator of the effectiveness of using safety technology and safe practices in saving lives and reducing injuries. The relative risk was determined as the ratio of the probability of injury or death in a crash for the exposed group (non-compliant vehicle design or unsafe practice) versus the non-exposed group (compliant vehicle design or safe practice), as shown in eq. 1. For example, the relative risk of injury in a front collision while not wearing a seatbelt (exposed group) versus wearing the seatbelt (non-exposed group) would be the probability of being injured for non-seatbelt users divided by the probability of being injured for seatbelt users. Table 1 estimates the average relative risk associated with each technology based on previous research and literature reviews. Upper and lower ranges of relative risk estimated by different studies were considered in the sensitivity analysis.

$$RR = \frac{Probability\ of\ being\ injured\,(non - seatbet\ users)}{Probability\ of\ being\ injured\,(seatbelt\ users)} \tag{1}$$

2.4. Technology fitment rate and use

The technology prevalence and use were estimated based on a comprehensive approach that involved literature reviews, online searches, and communication with relevant institutions in the region, such as the Bureau of Philippine Standards and Malaysian Institute of Road Safety Research (MIROS), ASEAN NCAP, and Autoliv. Country-specific data on all technologies and safety best practice interventions were utilized when available and the average for other countries of similar income levels when not available. The average status of the

Table 1
Description of the regulations, relative risks, the average fitment rate of vehicle safety interventions, and the usage rate of each road user protective device.

Regulations	Description	Technology	Effected road user	Relative risk (References)	Average fitment and usage rates
UN R13H	Brakes for vehicles	Anti-lock Braking System (ABS)	All	[4,5,38,39]	30 %
UN R140	electronic stability control	Electronic Stability Control (ESC)	All	[7–9,38]	13 %
UN R14 UN R16	Seat belt anchorages Seat belts	Seat belts	Car occupants	[40,41]	75 %
UN R94	Occupant protection in the event of a frontal impact	front airbag	Car occupants	[14,38,42,43]	40 %
UN R95	Occupant protection in the event of a side impact	side airbag	Car occupants	[38,44,45]	10 %
UN R135	Protection against side impact against a pole	Side door impact bar Structure and side protectors Optimized Side Impact Protection System	Car occupants	[38]	75 % 5 %
UN R127	pedestrian protection	pedestrian protection	Pedestrians	[46,47]	10 %
UN R44	Child restraint systems	child restraint systems	Car occupants (0–12 years old	[48–51]	10 %
UN R22	Helmets and visors for motorcycle drivers and passengers	Motorcycle helmet (bicycle helmet)	Motorcyclist and bicyclists	[12,52–55]	83 %
UN R131 UN R152	Advanced emergency braking systems for heavy vehicles Advanced emergency braking systems for M1 and N1 category vehicles	Advanced Emergency Braking Systems (AEBS)	Pedestrians and car occupants	[24–26,56–58]	0%
EU 2019–2144	Lane keeping assistance	lane keeping assistance systems (including lane centering systems)	Car occupants	[26,29,31,58,59]	
UN R89	Speed limitation devices	Speed limitation devices	All	[32,36,60]	

current technology prevalence and use data are presented in Table 1. Estimates of the baseline prevalence of ADAS features (AEBS, LKA, and speed limitation systems) were set to zero. Upper and lower ranges of technology fitment and usage were considered in our sensitivity analysis (see Table A1 in the appendix for further details).

2.5. Crash configuration

Crash configuration refers to the type of road traffic crashes, such as frontal, side-impact, rear-end, run-off-road, and rollover crashes. It also refers to the type of road user involved in the crash, i.e., single-vehicle, multi-vehicle, car-to-pedestrian, car-to-motorcycle, and motorcycle-to-pedestrian crashes. Identifying crash configuration is critical for the accuracy of our analytical approach. This process entails an estimation of the proportions of deaths and injuries that occur in various traffic crashes. The benefit of a safety technology can then be estimated by identifying the percentage of crash configurations and the proportion of road users affected by that technology. Next, by applying the relative risk in all identified crash configurations, we determine the number of deaths and DALYs that would be averted by the technology use and fitment. Table 3 presents the proportions of fatalities and injuries associated with crash configuration and the technology sensitive to it.

2.6. Estimation of deaths and injuries reduction

We employed the population attributable fraction (PAF) to estimate the reduction in deaths and injuries resulting from the implementation of a specific technology or group of technologies [37]. The PAF represents the expected proportional reduction in deaths or injuries if the exposure to a risk factor were reduced to an alternative (counterfactual) distribution, as illustrated in Fig. 3. For instance, we estimated the reduction in deaths and injuries that would result from increasing seatbelt usage from 50 % to 100 %. To accurately determine the PAF value, it is essential to provide the following inputs:

- The number of deaths and injuries in the target population affected by the intervention, such as the proportion of vehicle occupants or pedestrians involved in collisions.
- Identification of crash configurations influenced by the technology, such as the impact of side impact optimization on injuries to vehicle occupants when the side of the vehicle is struck.
- Estimation of the technology's effectiveness in reducing deaths and injuries across various crash configurations (relative risk).
- Estimation of the prevalence of the technology in the vehicle fleet, including the proportion of vehicles currently equipped with the

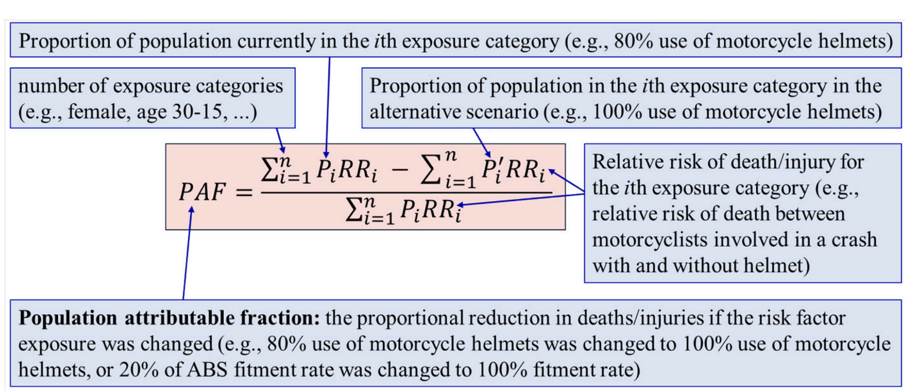

Fig. 3. Population Attributable Fraction (PAF) approach to calculate the reduction in deaths and DALYs when the technology fitment and use are changed to a different scenario (counterfactual).

technology and the expected proportion after full implementation (assumed to be 100 %).

However, the model inputs, including data on deaths, injuries, relative risk, technology prevalence, and usage, required several assumptions and the adoption of information from neighboring countries due to significant uncertainties and data unavailability. For instance, epidemiological reports from low-income and middle-income countries in the ASEAN region indicate that actual road traffic deaths are underreported by traffic police [61]. To address these uncertainties, we conducted a sensitivity analysis, reporting minimum and maximum values derived from modeling all possible combinations of the main estimates. We utilized the 95 % uncertainty confidence interval of the Global Burden of Disease (GBD) and national estimates from 2019 to account for variations in baseline traffic deaths and injuries, as well as the proportions of deaths and injuries among different road user categories (pedestrians, bicyclists, motorcyclists, and vehicle occupants).

The relative risk ratios were obtained from various evaluation methods, including field tests, experimental tests, and real crash data. However, discrepancies within these reports led to substantial variations in the estimated relative risks associated with the selected safety technologies. These variations were further influenced by the proper use of interventions such as seatbelts, child restraints, and helmets, as well as drivers' ability to disable certain protection systems (e.g., AEBS, LKA, and speed limiters). We applied the mean relative risk from the most robust evaluations as the main estimate and included the maximum and minimum of the 95 % confidence interval in the sensitivity analyses. For technology prevalence and usage, we assumed minimum and maximum estimates based on the penetration of these technologies in new vehicle fleets sold between 2018 and 2019. This information was available for Malaysia, Indonesia, and Thailand. For other countries where technology prevalence is unknown, we applied the average prevalence and usage rates from these three countries.

3. Results

Fig. 4 presents the results obtained under the assumption that all ASEAN vehicles comply with the priority eight UN vehicle safety standards and that all road users comply with safety best practices of appropriate and full use of protective devices (for detailed results, refer to Figs. A2 and A3 in the appendix). Our estimates suggest significant reductions in deaths and DALYs from overall improvements in vehicle safety design and safety best practices in all ASEAN countries. The results reveal that a total of 34,373 lives could be saved and 2,553,305 DALYs would be averted by using technologies that were invented in the middle of the last century. The gains are the highest for Malaysia (37.53 % fewer deaths and 40.29 % fewer DALYs) and the lowest for Brunei (30.27 % fewer deaths and 35.02 % fewer DALYs). The largest reductions in deaths and DALYs would be achieved in Indonesia (12,986 fewer deaths and 1,030,872 fewer DALYs) followed by Viet Nam (8845 fewer deaths and 664,250 fewer DALYs) and Thailand (7227 fewer deaths and 464,439 fewer DALYs). Results of the sensitivity analysis are illustrated in error bars, while detailed upper and lower values are presented in Tables A2 and A3 in the appendix.

Such trends could be attributed to several factors, such as country income level, population, and the availability and use of the safety technologies. However, death rates (per 100,000 population) seem to have less effect on the reduction percentage of the safety interventions. For example, while Thailand had the highest death rate followed by Viet Nam and Singapore had the lowest, Malysia had the highest reduction percentage followed by Thailand and Brunei had the lowest. In terms of number of lives saved by the technology, Indonesia had the highest gain followed by Viet Nam and Brunei had the lowest. It is difficult to explain this result, but it might be related to the transportation habits (walking, cycling, driving, and other means of commuting), the country's compliance with UN regulations (e.g., the UN conventions of 1958 and 1998 on wheeled vehicle equipment and parts), in addition to traffic law enforcement for wearing protective devices.

Fig. 5 shows the effectiveness of each safety technology in death and DALYs reduction. Among the eight proven vehicle safety technologies, ESC, including the safety benefits of ABS, is the most effective at reducing deaths by 23 % and DALYs by 20 %. There are three likely causes for such differences. Firstly, ESC and ABS are active safety

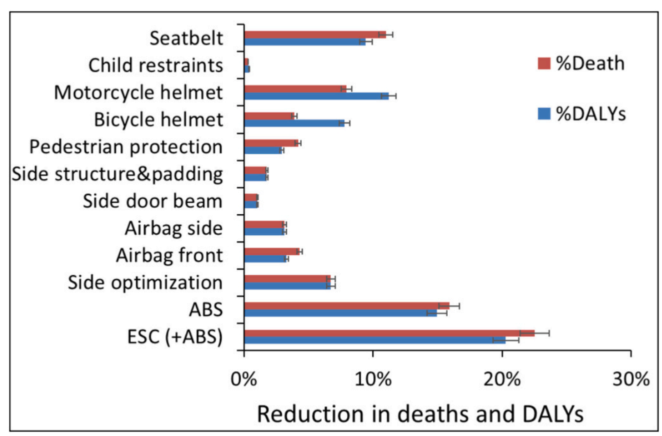

Fig. 5. Mortality and disability reduction in the ASEAN region by priority UN vehicle safety technologies and protective devices. Error bars represent the upper and lower ranges of the sensitivity analysis.

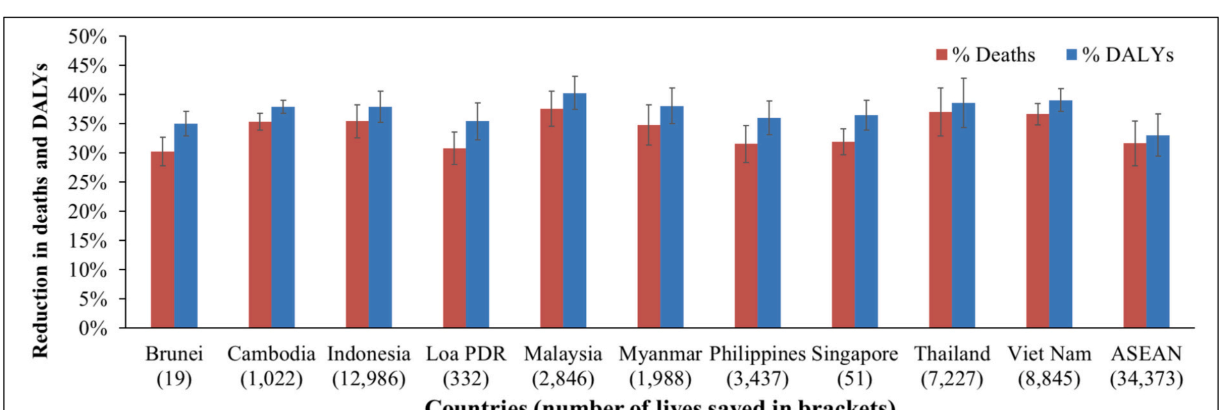

Fig. 4. Overall reduction in road traffic deaths and health burden (DALYs) by the eight proven vehicle safety technologies and protective devices in each country and the ASEAN region (excluding the safety benefits of AEBS, LKA, and speed limitation). Error bars represent the upper and lower ranges of the sensitivity analysis.

systems that enhance vehicle control and crash avoidance, thereby complementing passive safety systems. Secondly, unlike occupant-specific safety technologies such as seatbelts, airbags, and helmets, ESC and ABS offer benefits to all road users, extending beyond the protection of the vehicle occupants alone. Thirdly, ESC and ABS are sensitive to wider crash configurations (see Table 2).

Among the investigated protective devices, seatbelts can provide the highest safety benefits (11 % fewer deaths and 9.5 % fewer DALYs). Helmets also provide substantial benefits for vulnerable road users. Appropriate use of motorcycle helmets can reduce motorcyclist deaths by 8 % and DALYs by 11 %, while bicycle helmets can reduce bicyclist deaths by 4 % and DALYs by 8 %. It should be noted that the low effectiveness of child restraints (averaged 1 % fewer deaths and DALYs) compared to seatbelts is attributed to the fatality rate of occupants aged 0–12 years old (child restraints users) compared to older age groups who can be benefited from seatbelts. Accumulatively, helmets can provide greater protection for VRUs than that provided by seatbelts and child restraints for car occupants.

Fig. 6 illustrates the percentage reduction in deaths and DALYs by AEBS, LKA, and Speed Limitation–when implemented in the entire ASEAN vehicle fleet. Among the investigated technologies, speed limitation demonstrates the most substantial effect, with an overall reduction in deaths of approximately 30 % and DALYs of 28 % in the region. AEBS and LKA also show promising potential, with an estimated additional reduction of 9–11 % in deaths and DALYs by each technology. However, it is essential to consider the substantial interactions among active safety systems, as some systems mitigate injuries in the same crash configuration and when combined with other vehicle safety technologies. For example, vehicles equipped with ESC are also equipped with ABS, and both ABS and ESC are integrated into AEBS and LKA systems. Ideally, vehicles equipped with ADAS features are supposed to be equipped with the priority UN vehicle safety standards and associated existing technologies. Therefore, the data in Fig. 6 shows the estimates of the additional benefits of AEBS and LKA, excluding the benefits from ABS, ESC, and other interacting technologies.

Overall, these results indicate a potential to save approximately 63,898 lives and reduce health loss by averting 4,588,524 DALYs through improving vehicle safety design, using protective devices, and implementing driver assistance systems (Fig. 7). Moreover, the overall reduction does not represent an average number or cumulative percentage of applying all technologies, as it has been modeled while considering the interactions and correlations among the investigated safety technologies. The most notable finding in Fig. 7 is that adhering to the priority UN safety standards, safety best practices, and speed limitations could lead to reducing half of road traffic deaths and disabilities. Additionally, a closer inspection of the figure shows that the greatest benefits of all technologies are provided for VRUs–pedestrians, cyclists, and motorcyclists–compared with vehicle occupants.

For all ten countries, the reductions in deaths and DALYs are

Table 2
Proportions of deaths and injuries associated with the type of traffic crashes and the relevant safety technology.

Crash configuration	Proportions		Technology
	Fatalities	Injuries	
Run-Off-road	0.353	0.141	ABS, LKA
Multi-Vehicle	0.586	0.840	ABS, ESC, AEBS
Rollover	0.112	0.028	ESC, LKA
Single-vehicle (non-rollover)	0.312	0.141	ESC, LKA
Frontal	0.540	0.280	Frontal airbag,
Side impact	0.250	0.337	Side airbags, Side-Door-Beam, Side Structure and Padding
Rear impact	0.060	0.336	Head restraints, AEBS
Car-to-pedestrian		0.51	Front-end design (Car crashworthiness design), AEBS

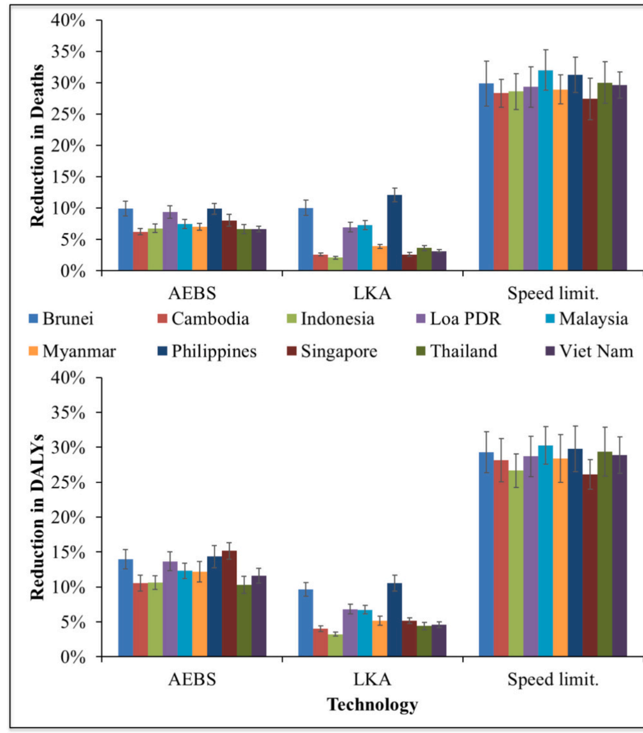

Fig. 6. Estimates of the effect of driver assistance systems on mortality and health loss (DALYs) caused by road traffic crashes in each country. Error bars represent the upper and lower ranges of the sensitivity analysis.

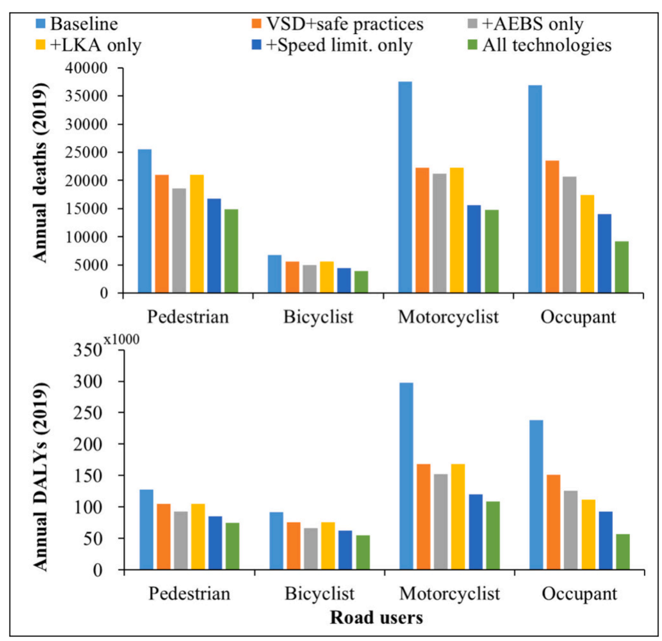

Fig. 7. Estimates of the overall effect of vehicle safety design (VSD), protective devices, and ADAS on reducing the total road traffic fatalities and disabilities categorized by road user type in the ASEAN region.

immense and can lower the road traffic death rates to the level of high-income countries with low death rates (e.g., Europe). Despite the well-documented and substantial advantages brought about by advancements in vehicle safety design, extensively supported by numerous research papers as a pivotal catalyst in achieving significant reductions in traffic fatalities across numerous high-income nations, there remains a noticeable lack of attention devoted to vehicle safety technologies within global road safety initiatives. Therefore, our findings emphasize the urgent need to prioritize and invest in improving vehicle safety design, promoting the use of protective devices, and incorporating safety-critical driver assistance features as the most effective and expedient approach to achieve the Sustainable Development Goals for road safety. They can inform decision-making, regulatory efforts, and stakeholders about the most effective strategies to address road traffic safety issues. Table 3 prioritizes key risk factors based on their effectiveness in reducing road traffic deaths and injuries in each ASEAN country, allowing each country to allocate resources to address these risk factors based on their priorities.

4. Discussion

The effectiveness of vehicle safety technologies and protective devices in reducing road traffic deaths and disabilities is well-documented in the literature. This study aimed to assess the impact of adopting UNECE regulations and emerging technologies on road traffic fatalities and disabilities in ten ASEAN countries. Among the eight proven vehicle safety technologies, Electronic Stability Control (ESC), which incorporates Anti-lock Braking Systems (ABS), achieved the highest reduction in road traffic deaths (23 %) and Disability-Adjusted Life Years (DALYs) (20 %). Following ESC, seatbelts reduced deaths by 11 % and DALYs by 9.5 %, full-face motorcycle helmets reduced deaths by 8 % and DALYs by 11 %, and vehicle side-impact optimization reduced both deaths and DALYs by 7 %. Although other safety technologies also contribute to reducing crash fatalities and injuries, their real-world benefits are maximized when integrated into the overall vehicle design. For instance, vehicle side-impact optimization, including side-door beams, side structure padding, and side airbags, offers greater protection collectively than each component individually.

Emerging technologies introduced in user cars since 2003, such as Autonomous Emergency Braking Systems (AEBS) and Lane Keeping Assist (LKA), have shown potential in reducing traffic crashes and mitigating crash severity. Our findings indicate that widespread implementation of AEBS and LKA in the ASEAN fleet could save thousands of lives and reduce health losses. However, the real-world benefits of AEBS and LKA might be underestimated due to several factors. Firstly, the performance and capabilities of these systems have significantly improved in recent versions compared to earlier ones. Secondly, even if equipped, users can deactivate these systems due to personal preferences or perceived inconvenience. Thirdly, the benefits of driver assistance systems are more apparent when they are widely adopted across the vehicle fleet.

Table 3
Prioritizing main key risk factors based on their effectiveness for reducing road traffic deaths and injuries in each ASEAN country.

Country	priority 1	priority 2	Priority 3	priority 4
Brunei	ESC with ABS: 20.46 %	Seat belts: 8.71 %	Side optimization: 7.66 %	Frontal airbag: 6.36 %
Cambodia	ESC with ABS: 29.73 %	Motorcycle helmet: 24.33 %	Seat belts: 4.40 %	Side optimization: 1.98 %
Indonesia	ESC with ABS: 29.48 %	Motorcycle helmet: 16.19 %	Crashworthiness: 2.86 %	Bicycle helmets: 1.88 %
Lao PDR	ESC with ABS: 19.1 %	Seat belts: 17.2 %	Side optimization: 10.7 %	Frontal airbag: 6.9 %
Malaysia	ESC with ABS: 29.01 %	Seat belts: 6.40 %	Motorcycle helmet: 5.82 %	Side optimization: 5.56 %
Myanmar	ESC with ABS: 28.45 %	Motorcycle helmet: 26.76 %	Seat belts: 7.5 %	Side optimization: 2.98 %
Philippines	ESC with ABS: 20.7 %	Side optimization: 9.24 %	Frontal airbag: 7.67 %	Seat belts: 7.34 %
Singapore	ESC with ABS: 25.55 %	Motorcycle helmet: 16.55 %	Crashworthiness: 5.36 %	Bicycle helmet: 3.75 %
Thailand	ESC with ABS: 30.40 %	Motorcycle helmet: 24.67 %	Seat belts: 4.08 %	Side optimization: 2.87 %
Viet Nam	ESC with ABS: 30.43 %	Motorcycle helmet: 12.33 %	Seat belts: 4.87 %	Side optimization: 2.38 %

Extrapolating these findings globally should be approached with caution due to varying crash configurations among countries. For example, in India, the proportion of cars as impacting vehicles is small compared to the proportions of pedestrians, bicyclists, and motorcyclists being struck by buses, trucks, or other motorcyclists [62]. Thus, improvements in light vehicle front-end design for pedestrian protection might have less impact in such contexts. Although difficult to implement in low- and middle-income countries, AEBS with the capability to detect Vulnerable Road Users (VRUs) could have a stronger effect if also equipped in heavy vehicles like buses and trucks. In this study, we categorized safety effects by road user types and further prioritized them to help these countries allocate their resources effectively to address traffic safety issues. For example, our results suggest that deaths and disabilities could be halved if each country complied with priority UN safety standards for vehicle design and if all road users adhered to appropriate use of protective devices and speed limits. Implementing these procedures is more cost-effective and efficient than adopting emerging technologies like AEBS and LKA.

A notable finding is the significant impact of speed limitation systems on all road users, surpassing the benefits of active safety systems like ABS, ESC, AEBS, and LKA. According to our estimates, ASEAN countries could achieve the goal of halving road traffic deaths and injuries by 2030 by implementing the eight proven vehicle safety technologies, enforcing the use of protective devices, and complying with speed limitation controls. However, the effectiveness of speed limitation systems is influenced by factors such as impact speed, age group, gender, and the use of protective devices. For instance, the risk of fatal injury to a pedestrian struck by a car traveling at 40 km/h is higher for those aged 70+ compared to those aged 30–40. Our study could not categorize road traffic crashes by the speed at which they occurred. Additionally, our estimations assumed all road users appropriately used protective devices and that all cars complied with priority UN safety standards.

This study is limited by the lack of detailed crash configuration data and information on the availability of technology in the region. Although we used crash configurations from the USA, Germany, and Japan, which were not substantially different, countries with less developed roadway infrastructure might show larger differences. Furthermore, data on helmet types (full-face, open-face, or half helmets), quality (e.g., standardized), and appropriate use (e.g., fastened or not, and helmet size) were not available. The same issue applies to child restraint systems. Improper use of child restraints can increase the risk of death or serious injury among child occupants.

Further research is needed to determine the real-world effectiveness of emerging technologies (AEBS, LKA, speed limitation systems). These systems are influenced by several human-related and technical factors, such as user acceptance and variation in system capabilities among manufacturers. User acceptance directly affects the effectiveness of Advanced Driver Assistance Systems (ADAS) as drivers may disable AEBS, LKA, and other warning functions whenever they wish.

Although the results regarding speed limitation devices are promising, considering current speed regulations, the road traffic environment, and the accuracy of speed limit information, broad application of speed suppression control may not be accepted by users, leading to lower usage rates. It is desirable to decide the target roads for such devices by considering their social acceptability, effectiveness in reducing accidents, and the development and diffusion of the technology. One possible approach is to apply these devices to residential areas (e.g., Zone 30), areas with frequent accidents due to excessive speed, and general roads with many pedestrians. However, at this point, the necessary information to limit the range of application could not be reliably obtained, so the specification allows drivers to change the settings within a certain range without limiting the target roads.

Despite these limitations, this study provides evidence to support effective strategies for accelerating the implementation of the Global Plan for the Second Decade of Action for Road Safety 2021–2030 in LMICs.

5. Conclusion

This study has identified that more than 59 % of traffic deaths and disabilities could be prevented if all vehicles were fitted with standardized safety technologies and crash avoidance systems and all road users adhered to the safety best practices of using protective devices. The eight proven vehicle safety technologies that have been available since the 1960s could prevent more than 31 % of traffic deaths and disabilities. Using protective devices, such as occupant restraints and helmets, would save hundreds of lives and avert thousands of DALYs. Speed limitation would provide twice the safety benefits for all road users compared to more expensive technologies (AEBS and LKA). Although most of the investigated technologies are vehicle-specific, they have the potential to make the roads safer for vulnerable road users, such as pedestrians, bicyclists, and people with reduced mobility. Vehicle safety design and emerging technologies have the potential to alleviate the public health burden in low and middle-income countries and need to be prioritized in future practices, such as the SDG target for 2030. Findings of this study contribute to encourage regulatory efforts to enhance overall vehicle safety design.

CRediT authorship contribution statement

Husam Muslim: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Marko Medojevic:** Data curation, Resources. **Sandra Watanabe:** Investigation, Project administration, Writing – review & editing. **Hisashi Imanaga:** Conceptualization, Project administration, Supervision, Writing – review & editing. **Nobuyuki Uchida:** Conceptualization, Supervision. **Sou Kitajima:** Supervision, Writing – review & editing. **Genya Abe:** Conceptualization, Funding acquisition, Supervision.

Declaration of competing interest

All authors declare that they have no conflicts of interest.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.iatssr.2024.09.002.

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