



## Decade of Monitoring Road Safety Performance Indicators in the Republic of Serbia (2013–2022) – Lessons That We Learned

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### ABSTRACT

Road safety performance indicators (RSPI) provide essential insight into traffic safety beyond crash statistics, enabling a better understanding of risk factors and policy impacts. In this sense, it is important to determine how RSPIs are related to the outcomes of traffic crashes. This point was the aim of this research, which used data from the ten-year experience of monitoring RSPI in Serbia. Monitoring of road safety performance indicators began in 2013 at the level of 27 police administration units. The relationship between RSPI and the outcomes of traffic crashes was investigated by applying fixed-effects regressions and Mundlak correlated random-effects models for panel data. Results showed that the most significant relationships were observed in the RSPI of protective systems in vehicles (seatbelts, child restraint systems and helmets) and speeding in urban areas. On the other side, speed-related indicators in rural areas and indicators related to distraction had weaker associations with the outcomes of traffic crashes. The set of constructs obtained from observed RSPI explained around 37% of the variability in the total weighted number of traffic crash casualties, highlighting the need to include indicators from all other groups. The findings highlight the methodological and policy value of sustained RSPI monitoring and suggest improvements in indicator design, especially for vulnerable road users, distraction and emerging mobility modes. Finally, the study's results confirm the importance of monitoring and incorporating indicators from all groups to describe the road safety situation in a local entity accurately.

### KEYWORDS

road safety performance indicators; traffic crashes; monitoring; road safety; protective systems; panel data.

## 1. INTRODUCTION

Road safety is a global problem, with numerous indirect indicators that have been developed over the past two decades. The development of indirect indicators enables proactive action, identification of key areas for intervention and similar measures [1].

Within the European Union, common road safety indicators have been selected, such as indicators related to speeding, non-use of seat belts, child restraint systems, helmets, alcohol, distraction and others, which have been confirmed as significant in a large number of studies [2–4]. In general, the state of road safety can be described by direct and indirect measures [1]. Direct measures represent the outcomes of traffic crashes, while indirect measures try to describe the state of road safety more comprehensively through road safety performance indicators (RSPI). Thus, Hauer & Bonneson [5] and Elvik et al. [6] found that an increase in the average speed of the traffic flow by 5 km/h was associated with an increase in the number of injuries by 15% and fatalities by 27%. In addition, other characteristics of road traffic speed, such as speed dispersion of traffic flow and percentage of offences, are associated with traffic unsafeness [7–9]. On the other hand, some authors emphasise the different effects of speed on different road types, which is why they associate increased speeds in urban conditions with a significant increase in the rate of crashes [10].

Current studies estimate that seat belt use reduces the risk of severe injuries in road traffic by 40–50% for the driver and front passenger, while for rear-seat passengers, this value is 25–75% [11], and the risk of moderate injuries by 65% [12]. The importance of protective systems for traffic safety can be explained in the example of the European Union, where in 2012, 12,345 vehicle passengers died in crashes, while seat belts saved 8,600 passenger lives; that is, they reduced mortality by 41% [13]. Phone use is one of the greatest causes of distraction in road traffic [10, 14]. Distraction has a pronounced negative impact on traffic safety because it affects numerous driver performances, such as reducing the driver's visual performance, speed, headway, reaction time, lateral control, driver's cognitive overload, etc. [10].

When it comes to measuring indirect road safety indicators, these measurements are most often conducted on representative samples at the national level in European Union countries [3, 15] and in Western Balkan countries [16]. This approach provides sufficiently accurate values at the national level for each parameter. However, when the question of differences between regions or cities is raised, such an approach cannot provide an adequate answer. Measuring indirect indicators at the national level also does not allow for the identification of key areas for intervention in specific regions or cities. Measuring and comparing road safety indicators between police administrative units (PAUs) or cities is important in order to understand the specific characteristics of smaller entities and to improve road safety within those entities [15, 17, 18].

For this reason, the methodology for measuring indicators in the Republic of Serbia has, since 2013, required indicator values to be representative at the level of PAUs, and since 2019 at the level of cities and municipalities. Representative indicator values for each municipality/city or police administration enable more detailed analysis and monitoring of the relationships between direct and indirect road safety indicators for each entity.

To assess the relevance of RSPI in describing road safety, it is necessary to examine its relationship with direct measures. Therefore, systematic long-term monitoring of RSPI is of particular importance.

More favourable indicator values, as well as increases in indicator values, are associated in the literature with a safer traffic safety situation. To make such an assessment, it is necessary to monitor the relationship between indirect and direct indicators over a longer time period, such as a decade. In general, the relationship between indirect and direct indicators is explained by the direction and the strength of the association. Therefore, the starting hypothesis of this research is that more favourable values of RSPI in PAUs or cities must be associated with reductions in traffic crash casualties in these local entities.

The objective of this study is to quantify the relationship between selected groups, using fixed-effects and correlated random-effects panel regression. The data on traffic safety outcomes and RSPI were structured as a panel structure. In the first step, RSPIs were entered one at a time in the fixed-effects panel regression models to mitigate multicollinearity. As a robustness check, we additionally applied a Mundlak correlated random-effects (within-between) specification, which preserves both within-district temporal variation and between-district differences, and allows the simultaneous inclusion of multiple correlated RSPI that were first grouped into latent factors using confirmatory factor analysis (CFA). The key indicators monitored in the Republic of Serbia are consistent with those measured in EU countries. Therefore, this study can contribute to a better understanding of RSPI effects, their relationship with traffic crash consequences, and the further development of new indicators. The strength of the relationship between direct and indirect traffic crash outcomes enables a reassessment of the existing indicators.

In addition, the paper presents an overview of trends in crash outcomes and RSPI, as well as key recommendations derived from long-term monitoring experience. These insights may support countries in achieving international road safety goals, including those of the United Nations [19], such as Target 3.6 and Vision Zero [20]. Although the analysis focuses on Serbia, the findings are relevant beyond the national context, as the country represents a typical road safety environment for low- and middle-income countries where comprehensive road safety monitoring systems are still being established.

## 2. DATA AND METHODS

### 2.1 Data

#### *Traffic crashes*

Data about the outcomes of traffic crashes in Serbia are publicly available in the open database of the Road Traffic Safety Agency. This database follows the Common Accident Data Set (CADaS) protocol developed by the European Commission [21] and can be accessed at the following link: <http://bazabs.abs.gov.rs/absPortal/>. Like all administrative crash databases, the CADaS-based data have some limitations and may include gaps for some descriptive variables. However, the present study relies on the annual number of recorded outcomes (i.e. event occurrence/count), which is consistently available in the database and does not require clarification. The available data have been used to analyse, monitor and improve the road safety system in Serbia. In addition, the data were exploited for previous scientific studies [22–27].

This study used traffic crash data for the ten years from 2013 to 2022. The observation period includes the COVID-19 years (2020–2021), during which traffic volumes and mobility patterns differed from typical conditions. These changes may have influenced traffic crash outcomes observed in those years. Data were extracted for the national level and the level of police administration units (PAUs). In addition to general data on the outcomes of traffic crashes (number of fatalities, seriously injured and slightly injured), we extracted data on specific categories of road users: pedestrians, cyclists, motorised two-wheelers, passengers in passenger cars and children. To present the outcomes of traffic crashes into a single value, we calculated the weighted number of casualties using the coefficients recommended by the Road World Association – PIARC [28]. According to these recommendations, the fatality is multiplied by the coefficient 99, the seriously injured by the coefficient 13, and the slightly injured by the coefficient 1. In this way, all the outcomes of traffic crashes are levelled to a unique value – the number of slightly injured. The final list of considered variables related to the final outcomes of traffic crashes with codes is presented in *Table 1*.

*Table 1 – The list of variables related to traffic crashes' outcomes*

Code	Variable	Period
TAF_1	Total weighted number of casualties	2013–2022
TAF_2	The weighted number of injured pedestrians and cyclists	
TAF_3	The weighted number of injured motorised two-wheelers	
TAF_4	The weighted number of injured passengers in passenger cars	
TAF_5	The weighted number of injured children	

#### *Road safety performance indicators*

Monitoring of RSPI in Serbia began in 2013. The COVID-19 period (2020–2021) was characterised by atypical traffic conditions and interruptions in RSPI measurement, particularly for speed-related indicators (no measurement in 2020), which may have influenced the observed results. At the beginning (2013–2018), RSPI was measured at the level of 27 PAUs. Starting in 2019, the measurement of RSPI was carried out at the level of 161 local communities (each PAU consists of three to 17 local communities). Prior to this transition, a pilot RSPI measurement was conducted in 2018 to evaluate the consistency between local-level measurements and aggregated PAU-level values, with positive results supporting the methodological shift. RSPI were collected on an annual basis, resulting in repeated yearly observations for each unit over the ten-year study period. Results at the level of local communities can be merged to obtain values at the level of PAUs, and results at the level of PAUs can be aggregated to obtain values for the national level. The data on the value of RSPI in

the Republic of Serbia are publicly available at the following link: <http://bazabs.abs.gov.rs/smartPortal/indikatori>. Although the ETSC framework includes additional important indicators, such as alcohol-related behaviour, vehicle safety standards (e.g. Euro NCAP) and road infrastructure safety, these indicators were not included in the present analysis due to data availability constraints. Their monitoring and data collection fall primarily under the responsibility of enforcement and regulatory authorities, and consistent, publicly accessible time series are currently not available.

During the first year, RSPI related to protection systems was investigated for all categories of vehicles (except buses). In the following year, the monitoring of RSPI related to speed, distraction and safety systems on the front seats of the bus was started. Measurements were taken once a year. The list of the most important RSPI that were the subject of this study is presented in *Table 2*.

Trained researchers measured RSPI in accordance with the recommendations of the SAFETYNET project [4]. In brief, the measurement of RSPI related to protective systems and distraction for each unit (PAU or local community) was carried out in the following conditions: during daylight hours (08:00–12:00 or 13:00–18:00), on the mid-days of the week (Tuesday–Thursday) and in different environments (urban, rural and highway). The selection of vehicles was made using random selection. The sample size depends on the RSPI type and at the national level ranges from several thousand (RSPI\_7) to several hundred thousand (RSPI\_1).

The measurement of RSPI related to speed was slightly different. These RSPI were measured at two times of the day: daytime (09:30–15:30) and night (22:00–06:00). Speed measurements were conducted only at sites that fulfilled strict criteria. Locations had to be on straight road sections with a surface in good condition and with road conditions that permitted speeding. A slight longitudinal slope of up to 5% was acceptable. Each site was required to be at least 500 m from intersections, traffic calming devices, road works or pedestrian crossings, and at least 1,000 m from changes in speed limits. In addition, measurement points were selected away from work zones, parking areas or other roadside attractions, as well as from locations where police usually enforce speed. The sample size depends on the vehicle and at the national level ranges from several thousand (RSPI\_14) to several hundred thousand (RSPI\_9).

*Table 2 – The list of representative road safety performance indicators*

RSPI category	RSPI list	Period
Protective systems	RSPI_1 - % of seat belt use at front seats in passenger cars (PCs) (<3.5t)	2013–2022
	RSPI_2 - % of seat belt use at rear seats in PCs (<3.5t)	
	RSPI_3 - % of seat belt use at front seats in heavy goods vehicles (HGVs) (>3.5t)	
	RSPI_4 - % of seat belt use at front seats in buses	2014–2022
	RSPI_5 - % of children using child restraints up to 3 years old	2013–2022
	RSPI_6 - % of children using child restraints from 4 to 12 years old	
	RSPI_7 - % of helmets used by drivers of mopeds	
	RSPI_8 - % of helmets used by drivers of motorcycles	
Speed	RSPI_9 - % of drivers of PCs exceeding the speed limit in urban areas (UR)	2014–2019 and 2021–2022
	RSPI_10 - % of drivers of PCs exceeding the speed limit in rural areas (RU)	
	RSPI_11 - % of drivers of HGVs exceeding the speed limit in UR	
	RSPI_12 - % of drivers of HGVs exceeding the speed limit in RU	
	RSPI_13 - % of drivers of mopeds exceeding the speed limit in UR	
	RSPI_14 - % of drivers of mopeds exceeding the speed limit in RU	
	RSPI_15 - % of drivers of motorcycles exceeding the speed limit in UR	
	RSPI_16 - % of drivers of motorcycles exceeding the speed limit in RU	
Distraction	RSPI_17 - % of drivers of PCs who do not use a mobile phone	2014–2022
	RSPI_18 - % of drivers of HGVs who do not use a mobile phone	
	RSPI_19 - % of drivers of buses who do not use a mobile phone	

## 2.2 Analysis

The analysis was conducted using two groups of variables defined at the level of police administration units (PAUs). The dependent variables were the outcomes of traffic crashes, represented by weighted indices of casualties (*Table 1*). The independent variables were road safety performance indicators (RSPI) listed in *Table 2*. By linking RSPI to crash outcomes, the models aim to identify the extent to which improvements in safety performance are associated with reductions in casualties.

Data on traffic crash outcomes and RSPIs were structured as a short panel, with 27 PAUs observed over a 10-year period. As the number of cross-sectional units substantially exceeds the number of time periods, Driscoll & Kraay [29] recommend using panel data regression models with fixed effects. Hoechle [30] noted that this approach effectively addressed the problems of cross-sectional correlation and heteroskedasticity while also considering applicability and robustness. The panel data regression model with fixed effects can be described as follows [31]:

$$(y_{it} - \bar{y}_i) = \beta_1(x_{it} - \bar{x}_i) + (u_i - \bar{u}_{it}) \quad (1)$$

or

$$\dot{y}_{it} = \beta_1 \dot{x}_{it} + \dot{u}_{it} \quad (2)$$

where  $\dot{y}_{it}$  is the time-demeaned data on the dependent variable  $y$ , and similarly for  $\dot{x}_{it}$  (independent variables) and  $\dot{u}_{it}$  (“usual” error term). This specification estimates the effects of time-varying RSPIs while removing all time-invariant differences across PAUs (e.g. geographic characteristics).

To obtain a clear interpretation of the association between each individual RSPI and fatal and serious injury outcomes, we first estimated a set of fixed-effects models that included one RSPI at a time. This approach avoids the multicollinearity issues that would arise if multiple highly correlated RSPIs were included simultaneously. In addition, indicators were excluded from models where no logical relationship with the corresponding crash outcome existed (e.g. protective-system RSPIs for pedestrian/cyclist outcomes).

However, fixed-effects models cannot capture between-PAU variation nor jointly estimate multiple correlated RSPIs. Therefore, to complement the single-indicator fixed-effects models and to assess robustness, we employed the Mundlak correlated random-effects models, which preserves both within- and between-PAU variation and allows simultaneous inclusion of several RSPIs.

To account for potential correlation between time-varying RSPIs and unobserved PAU-level heterogeneity, we applied the correlated random-effects specification proposed by Mundlak [32]. In this approach, the unit-specific effect is modelled as a function of the time averages of the covariates, allowing the estimation of both within- and between-PAU associations. The model can be written as:

$$y_{it} = \lambda x_{it} + \theta \bar{x}_i + u_i + \varepsilon_{it} \quad (3)$$

where  $y_{it}$  is the dependent variable for PAU  $i$  in year  $t$ ;

$x_{it}$  denotes the vector of time-varying RSPIs;

$\bar{x}_i = (1/T_i) \sum x_{it}$  represents the PAU-specific time-average of each RSPI;

$u_i$  is the residual unit-specific effect; and

$\varepsilon_{it}$  is the idiosyncratic error term.

The inclusion of  $\bar{x}_i$  relaxes the standard random-effects assumption by allowing correlation between the regressors and the unit-specific effect, yielding estimates that remain consistent even when the strict exogeneity assumption is violated [32, 33].

Before applying the Mundlak specification, the RSPIs were grouped into conceptually coherent latent factors. Their suitability for factor construction was evaluated through indicator reliability, internal consistency reliability, convergent validity and discriminant validity. Indicator reliability, assessed through the factor loadings (FL) of each item, reflects the degree to which an indicator explains the underlying construct [34]. Following Comrey and Lee [35], factor loadings above 0.63 are considered very good.

These latent factors were obtained using confirmatory factor analysis (CFA), an appropriate method when indicators are theoretically expected to represent shared underlying dimensions of road safety performance. CFA ensured that the grouped indicators demonstrated adequate construct validity and internal consistency, as evidenced by composite reliability (CR) and Cronbach’s alpha.

Internal consistency reliability was evaluated using Cronbach's  $\alpha$  and CR, both of which assess the degree of coherence among the items forming each construct. Values above 0.70 were considered acceptable [36]. In cases where a factor consists of only two items, a lower acceptable threshold of 0.50 was adopted. Convergent validity was examined using the average variance extracted (AVE), with thresholds above 0.50 indicating satisfactory levels [36]. This ensures that the items within a construct share a sufficient proportion of common variance.

Discriminant validity was confirmed by verifying that correlations between constructs were lower than the square roots of their respective AVE values. Finally, factor scores were computed for each construct. As noted by DiStefano, Zhu and Mîndrilă [37], factor scores represent composite variables that describe an observation's relative standing on each latent construct. These scores were derived using the regression method, based on a least-squares approach [38], producing standardised variables with a mean of 0 and a standard deviation of 1.

All statistical analyses were performed in STATA 17, with a 90% significance level adopted in fixed-effects and 95% significance level adopted in correlated random-effects models.

### 3. RESULTS

#### 3.1 General characteristics

##### *Traffic crash outcomes*

In traffic crashes in Serbia during the ten years (2013–2022), the officials noticed 5,619 fatalities, 33,261 serious injuries and 161,903 slight injuries. The weighted number of casualties decreased by 8.5% in 2022 compared to the base year. The highest levels of decrease in the weighted number of casualties were noticed among cyclists (25.5%), passengers in PV (22.2%) and pedestrians (20.4%). Conversely, the lowest levels of decrease in the weighted number of casualties were found among children (5.2%) and motorised two-wheelers (3.9%). The shares of the observed categories in the total weighted number of casualties during the whole period were between 3.4% for children and 22.8% for pedestrians. Although the overall trend shows progress (*Figure 1*), the reduction was uneven: vulnerable road users improved more slowly, while children remained a small but stable share.

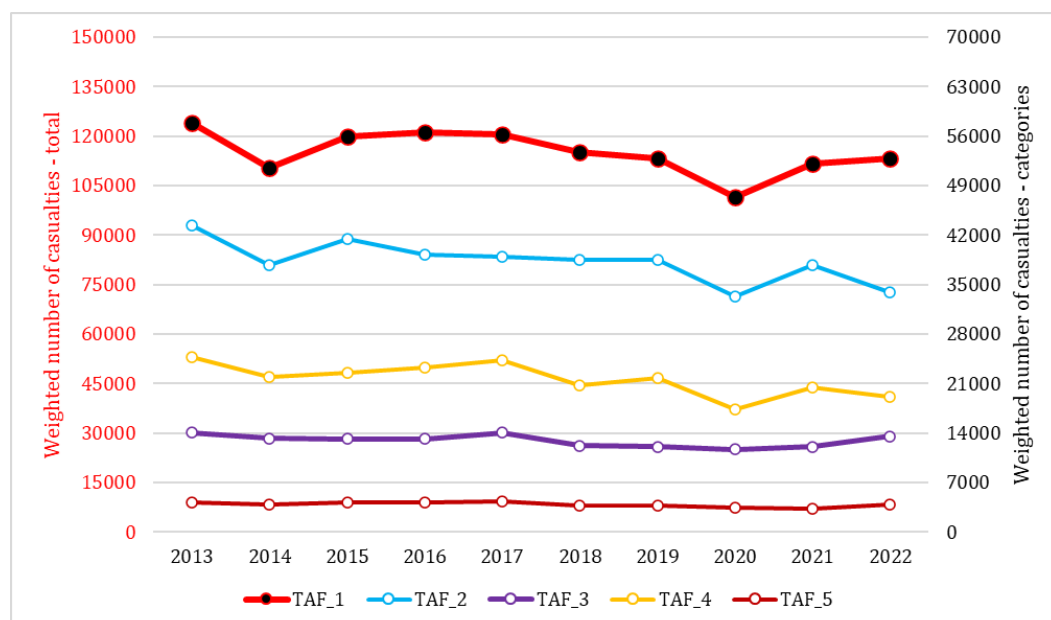


Figure 1 – Weighted number of casualties – total and per category

##### *Road safety performance indicators*

Almost all RSPI related to protection systems had a growth trend in the observed period (*Figure 2*). Seat belt usage in passenger cars increased by 16.2% in both the front and back seats. A specific characteristic of these two RSPI indicators is that their values remained constant during 2019–2022. In contrast, indicators related to seat belt use in the front seats of heavy goods vehicles and buses increased by 30.0% and 18.8%, respectively.

In the usage of child restraint systems, a growth of 39.0% in children under three years and 41.3% in children aged 4 to 12 years was recorded. As with seat belt usage in passenger cars, lower growth rates were noted after 2018. RSPI related to helmet use at motorised two-wheelers had a descending trend.

Speed-related RSPI were relatively constant in the observed period, regardless of vehicle category (Figure 3). In the category of passenger cars, a slight decrease in the percentage of exceeding the speed limit was recorded both in the urban and rural areas. In the urban areas, this percentage was significantly higher (8.5%) compared to rural areas (2.1%). Also, we noted a slight decrease in the rate of exceeding the speed limit for heavy goods vehicles in urban areas (4.6%), while an increase was recorded in rural areas (7.6%). A different state was found in the mopeds category, where a slight decrease in exceeding the speed limit was noted in urban areas (3.9%) and an increase in rural areas (6.3%). The percentage of motorcycles exceeding the speed limit decreased both in urban (3.4%) and rural areas (10.4%).

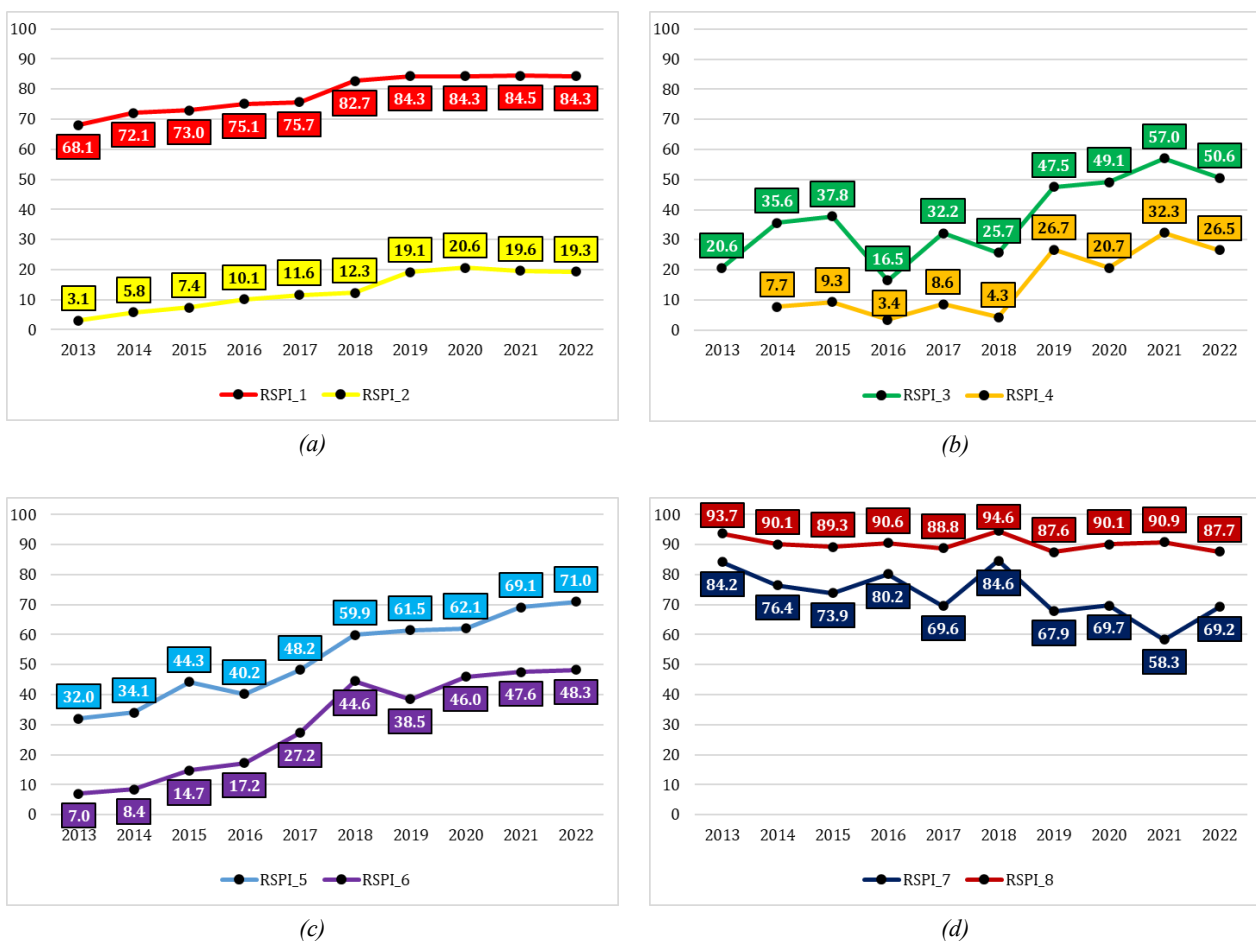


Figure 2 – The values of road safety performance indicators related to protective systems at the national level

The trends of RSPI that describe the driver’s distraction were different depending on the vehicle category (Figure 4). The value of the RSPI describing the non-usage of mobile phones by drivers of passenger cars is relatively constant, ranging from 94 to 97%. On the other hand, the non-usage of mobile phones by heavy goods vehicle and bus drivers was significantly lower compared to passenger car drivers. In addition, the trends of these RSPI have a slight decline.

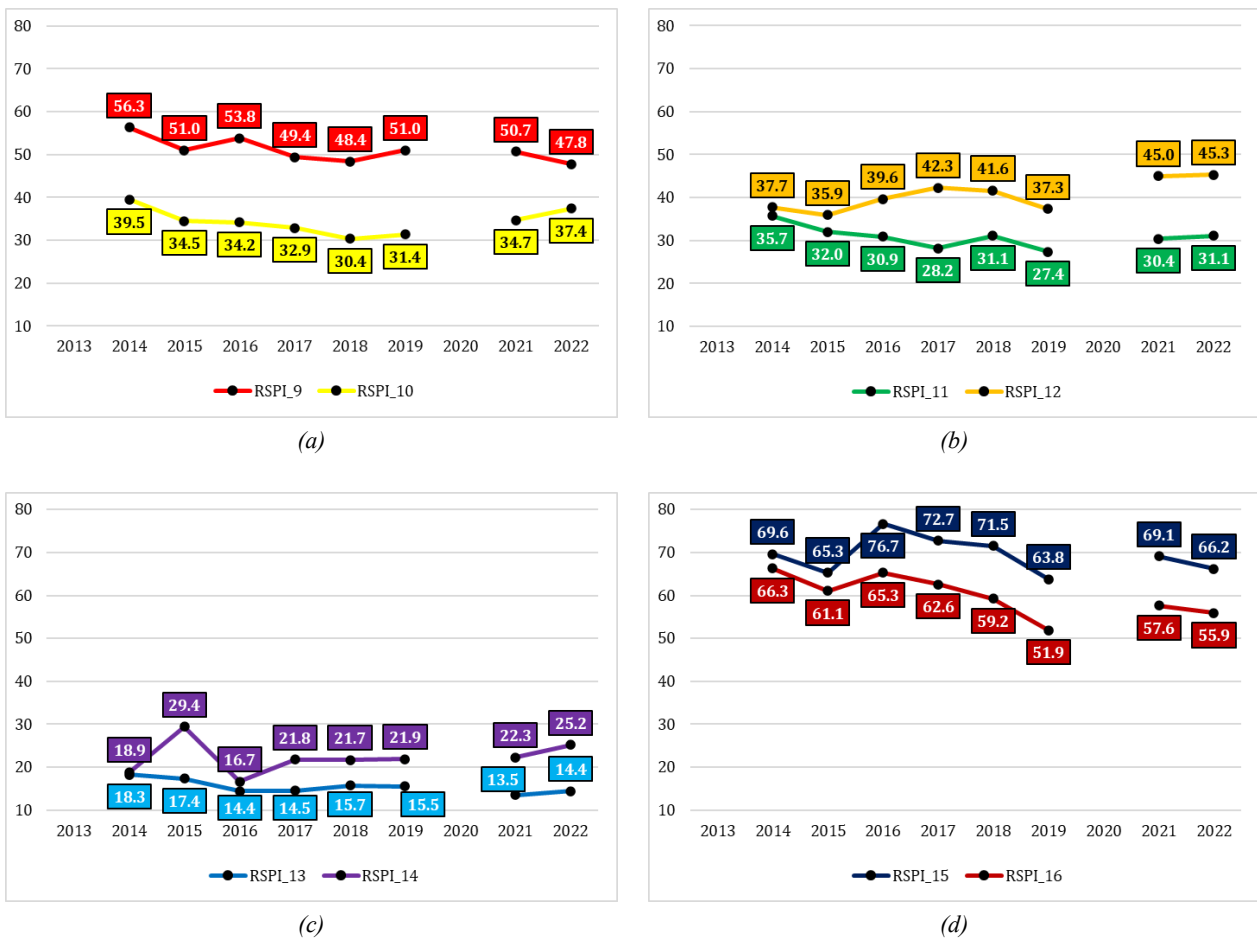


Figure 3 – The values of road safety performance indicators related to speed at the national level

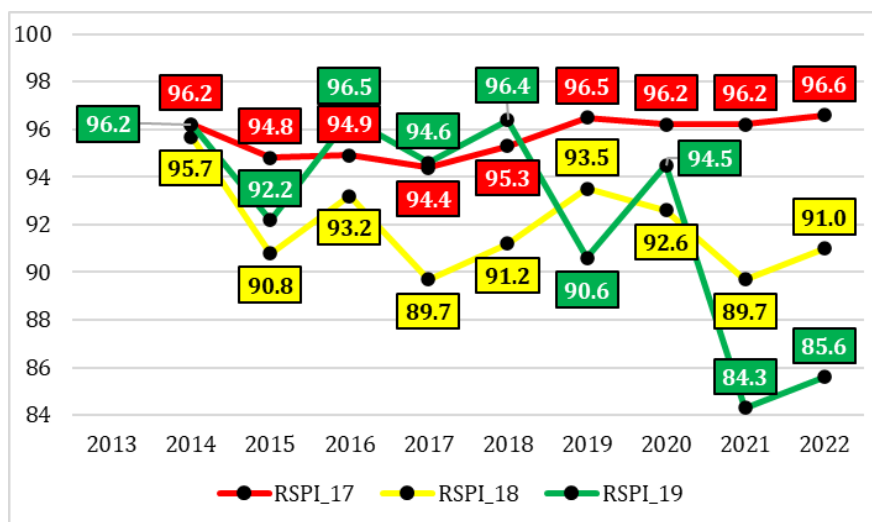


Figure 4 – The values of road safety performance indicators related to distraction at the national level

### 3.2 Models

#### Panel data fixed-effect models

Table 3 presents the values of regression coefficients obtained using panel data regression models with fixed effects. When the value of the regression coefficient is statistically significant ( $p < 0.10$ ), the  $R^2$  value is also presented. Green shading indicates expected and significant associations, red shading indicates significant but unexpected directions, while yellow shading denotes non-significant results.

Analysing the total traffic crash outcomes, we found that eight RSPI had an expected and statistically significant relationship with the traffic crash outcomes. Six of eight RSPI belong to the category of protective systems, among which the RSPI related to the usage of front seats in passenger and heavy goods vehicles were distinguished for their importance. The remaining two RSPI from the group were related to speed. Both RSPI described the behaviour of drivers on rural roads, the categories of heavy goods vehicles and motorcycles. All other RSPI did not show a statistically significant impact, except for the RSPI that described helmet usage by moped drivers. The direction of the relationship of this RSPI was not expected.

By considering the outcomes of traffic crashes related to pedestrians and cyclists, the RSPI that describes the use of protective systems and speed in rural areas (road sections where pedestrians and cyclists are not expected to participate) was not considered. Of the remaining seven RSPI, no one showed a statistically significant impact.

In the analysis of the motorised two-wheelers, only the RSPI related to helmet usage from the group of protective systems was considered. In addition to these two RSPI, all others from the groups related to speed and distraction were observed. Two RSPI that showed a statistically significant and expected direction of association were related to the speed of passenger cars and mopeds in rural areas.

The traffic crash outcomes related to passengers in passenger cars were not related to the RSPI that described the protective systems for other categories of vehicles, nor to the RSPI that described the speed of motorised two-wheelers. All considered, RSPI from the group of protective systems showed the expected and statistically significant relationship with the observed outcomes. From the other groups of RSPI, the RSPI describing the speed of passenger cars in rural areas showed a significant but unexpected relation.

Regarding children, RSPI related to protective systems in passenger cars, the speed of passengers and heavy goods vehicles, and distraction were considered. Expected and significant impacts were identified only for RSPI, describing the seat belt usage on the front seat of passenger cars and child restraint systems for older children (4–12 years). On the other hand, RSPI related to distraction showed an influence of an unexpected direction, while RSPI of speed did not show a statistically significant impact.

Table 3 – The values of the regression coefficients ( $\beta$ ) – TAF\_1-TAF\_5

RSPI		TAF_1		TAF_2		TAF_3		TAF_4		TAF_5	
		b	R <sup>2</sup>	b	R <sup>2</sup>	b	R <sup>2</sup>	b	R <sup>2</sup>	b	R <sup>2</sup>
Protective systems	RSPI_1	<b>-1859</b>	<b>0.059</b>	NR <sup>1</sup>		NR		<b>-627</b>	<b>0.036</b>	<b>-130</b>	<b>0.023</b>
	RSPI_2	<b>-1391</b>	<b>0.034</b>	NR		NR		<b>-550</b>	<b>0.029</b>	-47	NR
	RSPI_3	<b>-1072</b>	<b>0.088</b>	NR		NR		NR		NR	
	RSPI_4	<b>-489</b>	<b>0.016</b>	NR		NR		NR		NR	
	RSPI_5	<b>-738</b>	<b>0.044</b>	NR		NR		<b>-202</b>	<b>0.018</b>	-36	NR
	RSPI_6	<b>-537</b>	<b>0.032</b>	NR		NR		<b>-314</b>	<b>0.059</b>	<b>-39</b>	<b>0.013</b>
	RSPI_7	<b>555</b>	<b>0.021</b>	NR		47	NR	NR		NR	
	RSPI_8	517	NR	NR		157	NR	NR		NR	
Speed	RSPI_9	147	NR	-32	NR	123	NR	163	NR	37	NR
	RSPI_10	100	NR	NR		<b>157</b>	<b>0.018</b>	<b>-298</b>	<b>0.023</b>	26	NR
	RSPI_11	11	NR	182	NR	37	NR	116	NR	30	NR
	RSPI_12	<b>520</b>	<b>0.015</b>	NR		21	NR	-37	NR	15	NR
	RSPI_13	-174	NR	-134	NR	63	NR	NR		NR	
	RSPI_14	-445	NR	NR		<b>184</b>	<b>0.015</b>	NR		NR	
	RSPI_15	478	NR	192	NR	56	NR	NR		NR	
	RSPI_16	<b>460</b>	<b>0.022</b>	NR		-35	NR	NR		NR	
Distraction	RSPI_17	91	NR	-7	NR	35	NR	25	NR	<b>27</b>	<b>0.014</b>
	RSPI_18	84	NR	-7	NR	37	NR	28	NR	<b>31</b>	<b>0.016</b>
	RSPI_19	137	NR	22	NR	37	NR	52	NR	<b>32</b>	<b>0.015</b>

<sup>1</sup> Not relevant

*Confirmatory factor analysis*

Across all constructs, internal consistency reliability and convergent validity fall within recommended limits (Table 4). Cronbach’s  $\alpha$  ranges from 0.535 to 0.836, while CR values span from 0.811 to 0.924, confirming that the indicators within each construct show coherent relationships. In addition, AVE values exceed the minimum threshold of 0.50 for all constructs, indicating that each factor explains a substantial proportion of variance in its items and satisfies the standard for convergent validity. During the process of constructing the latent factors, several items did not load adequately onto their expected components (RSPI\_3, RSPI\_16 and RSPI\_19) and were therefore excluded from further analysis.

Table 5 evaluates the discriminant validity of the constructs. The diagonal elements represent the square roots of the AVE values, shown in bold, while the off-diagonal values denote inter-construct correlations. Discriminant validity is confirmed when the square root of a construct’s AVE exceeds all correlations with other constructs. This requirement is met for all constructs, so our factors.

Table 4 – Reliability and convergent validity of constructs

Factors	Item	Mean (SD)	FL	Cronbach’s $\alpha$	CR	AVE
<i>F_PS_vehicle</i>	RSPI_1	0.791 (0.084)	0.837	0.830	0.904	0.655
	RSPI_2	0.134 (0.079)	0.754			
	RSPI_4	0.176 (0.161)	0.717			
	RSPI_5	0.535 (0.179)	0.857			
	RSPI_6	0.322 (0.209)	0.871			
<i>F_PS_helmets</i>	RSPI_7	0.715 (0.170)	0.881	0.535	0.811	0.682
	RSPI_8	0.894 (0.100)	0.874			
<i>F_speed_urban</i>	RSPI_9	0.502 (0.224)	0.913	0.832	0.905	0.763
	RSPI_11	0.302 (0.154)	0.894			
	RSPI_15	0.692 (0.170)	0.811			
<i>F_speed_rural</i>	RSPI_10	0.346 (0.158)	0.927	0.836	0.924	0.859
	RSPI_12	0.407 (0.216)	0.927			
<i>F_speed_moped</i>	RSPI_13	0.151 (0.121)	0.838	0.577	0.825	0.702
	RSPI_14	0.223 (0.134)	0.838			
<i>F_distraction</i>	RSPI_17	0.957 (0.019)	0.764	0.691	0.866	0.764
	RSPI_18	0.921 (0.046)	0.764			

Table 5 – Discriminant validity of constructs

	<i>F_PS_vehicle</i>	<i>F_PS_helmets</i>	<i>F_speed_urban</i>	<i>F_speed_rural</i>	<i>F_speed_moped</i>	<i>F_distraction</i>
<i>F_PS_vehicle</i>	<b>0.809</b>					
<i>F_PS_helmets</i>	0.052	<b>0.826</b>				
<i>F_speed_urban</i>	0.005	0.086	<b>0.873</b>			
<i>F_speed_rural</i>	0.282	0.006	0.069	<b>0.927</b>		
<i>F_speed_moped</i>	-0.183	-0.059	0.184	-0.304	<b>0.838</b>	
<i>F_distraction</i>	-0.004	0.028	-0.176	-0.242	0.146	<b>0.874</b>

*Panel data Mundlak correlated random-effects models*

The dependent variables (TAF\_1–TAF\_5) were normalised using the population size of each PAU. This transformation was applied to obtain comparable values across PAUs, preventing larger PAUs from mechanically generating higher casualty counts. In addition, using a population-adjusted approach improves

model stability and strengthens the interpretation of Mundlak's within-between decomposition, since both short-term (within) and long-term structural (between) effects become more meaningful when expressed relative to the exposed population.

Across the five Mundlak correlated random-effects models (Table 6), the within and between  $R^2$  values show clear differences in explanatory power. Between  $R^2$  values (ranging from 0.25 to 0.62) are consistently higher than within  $R^2$  (typically below 0.04), indicating that most variation in traffic crashes' outcomes occurs across PAUs rather than over time within the same PAU. The strongest overall fit is observed in the model with all causalities, suggesting that the total casualty burden is most strongly associated with the factors obtained based on road safety performance indicators.

Regarding individual factors, the results consistently show that the between effects are more pronounced than the within effects. Factors related to the use of protective systems in vehicles ( $F\_PS\_vehicle$ ) and urban speeding ( $F\_speed\_urban$ ) most frequently exhibit significant associations with the outcomes. This practically means that PAUs, which, over the long term, maintain higher rates of protective system use in vehicles and lower proportions of speed-violating vehicles in urban areas, experience lower casualty risk.

The factor describing the use of protective systems showed a significant effect in all models in which it was included, whereas the urban speeding factor was insignificant only in the model describing casualties among children. On the other hand, factors incorporating rural speeding ( $F\_speed\_rural$ ) and distraction ( $F\_distraction$ ) did not demonstrate statistically significant effects in any model.

It is also important to note the presence of unexpected coefficient signs for the two factors related to the behaviour of powered two-wheelers ( $F\_PS\_helmets$  and  $F\_speed\_moped$ ). One plausible explanation for this finding is the very small share of powered two-wheelers in Serbia. Because their exposure is low, the safety benefits of correct behaviour (e.g. proper helmet use or compliance with speed limits) become statistically overshadowed when outcomes are aggregated at the PAU-population level. This phenomenon is consistent with previous findings [39], where road users with minimal traffic presence – such as powered two-wheelers – show weak or even counterintuitive associations with casualties.

Table 6 – Mundlak within-between effects for population-adjusted TAF outcomes

Variables	TAF_1	TAF_2	TAF_3	TAF_4	TAF_5
<b>Within effects (<math>\lambda</math>)</b>					
$F\_PS\_vehicle$	35.01 (24.68)	NR	NR	4.27 (8.46)	0.09 (3.75)
$F\_PS\_helmets$	17.40 (23.66)	NR	-0.96 (6.26)	NR	NR
$F\_speed\_urban$	56.18 (35.86)	11.13 (19.02)	18.87 (11.47)	19.12 (11.77)	2.83 (4.49)
$F\_speed\_rural$	32.80 (28.85)	NR	10.23 (6.35)	-0.53 (13.15)	2.35 (4.52)
$F\_speed\_moped$	18.18 (30.01)	6.65 (15.36)	1.97 (7.75)	NR	NR
$F\_distraction$	-22.08 (29.53)	-10.53 (10.73)	1.13 (6.08)	-5.49 (11.25)	4.42 (2.48)
<b>Between effects (<math>\theta</math>)</b>					
$F\_PS\_vehicle$	<b>-426.77 (132.81)</b>	NR	NR	<b>-71.54 (21.55)</b>	<b>-19.27 (7.02)</b>
$F\_PS\_helmets$	<b>313.97 (82.27)</b>	NR	-6.66 (15.10)	NR	NR
$F\_speed\_urban$	<b>223.99 (51.33)</b>	<b>72.26 (28.50)</b>	<b>21.30 (11.07)</b>	<b>48.14 (13.99)</b>	4.65 (2.48)
$F\_speed\_rural$	104.30 (59.68)	NR	14.78 (14.73)	6.56 (16.72)	2.92 (6.00)
$F\_speed\_moped$	<b>-169.94 (57.64)</b>	<b>-49.53 (19.94)</b>	-10.34 (7.73)	NR	NR
$F\_distraction$	-21.17 (57.98)	-8.82 (38.86)	-17.98 (18.40)	12.70 (20.68)	-0.36 (7.31)
Constant	1686.02 (39.20)	530.66 (19.74)	187.77 (8.85)	334.61 (12.83)	58.69 (2.75)
<b><math>R^2</math></b>					
Within	0.036	0.008	0.026	0.011	0.009
Between	0.611	0.323	0.343	0.373	0.283
Overall	0.370	0.152	0.143	0.143	0.048

## 4. DISCUSSION

Based on the analysis of the outcomes of traffic crashes in Serbia, a clear downward trend can be observed over the analysed period. According to the data of the Road Traffic Safety Agency [40], this trend was primarily driven by a decrease in the number of fatalities and seriously injured persons. During the analysed period, the number of fatalities decreased by 14.9%, while the number of seriously injured decreased by 3.8%. At the same time, the number of slightly injured increased by 4.7%, which partially reflects improved survival rates and injury outcomes rather than an overall deterioration of safety conditions. Comparable reductions in fatalities have also been recorded in several European countries, such as France, Italy, Portugal and Hungary, during the same period [41].

The Road Safety Strategy of the Republic of Serbia 2023–2030 [42] identifies several systemic activities that have contributed to these positive outcomes, including the establishment of an integrated traffic crash database, continuous training of key stakeholders, regulatory amendments, application of modern infrastructure safety tools, scientific research and improved equipment of traffic police units. In addition to these system-level measures, improvements in road users' behaviour represent an important complementary mechanism through which road safety outcomes can be improved.

An analysis of the trends in the considered RSPI indicates that the most pronounced behavioural improvements were achieved in the domain of protective systems. Although Serbia still lags behind leading road safety countries such as Sweden, Norway and the United Kingdom [41], the largest relative progress was recorded in the use of child restraint systems. In contrast, no stable and consistent improvement trend was observed for indicators related to speed and driver distraction, while seat belt use among rear-seat passengers remains particularly low. These findings indicate that behavioural change has been uneven across road safety domains.

Results from the five Mundlak correlated random-effects models suggest that differences in traffic crash outcomes are driven primarily by long-term, structural disparities between PAUs, rather than by short-term year-to-year fluctuations in RSPIs within a given PAU. Models indicate that PAUs with persistently better safety-related conditions and behaviours tend to have consistently better crash outcomes, while short-term fluctuations in observed RSPI levels within a PAU are not large enough to translate into detectable year-to-year changes in outcomes. Among the examined indicators, those related to vehicle protective systems and speed in urban areas emerged as the most influential. The effect of these RSPI is consistent with prior evidence, which has also reported strong associations between RSPI and improved traffic crash outcomes [43, 44]. On the other hand, several associations showed unexpected directions for indicators related to powered two-wheelers (e.g. helmet use and moped speeding). These results may reflect the relatively low prevalence and exposure of powered two-wheelers on Serbian roads, which can yield less stable estimates and counterintuitive aggregate relationships. Similar patterns have been noted in prior studies [39].

When considering specific categories of crash participants, the primary focus is on pedestrians and cyclists. Among the observed RSPIs, statistically significant associations with crash outcomes for these road users were found only for RSPIs related to speeding in urban areas. However, pedestrian and cyclist casualties should be interpreted in light of the fact that a substantial share of these crashes is attributable to pedestrians' and cyclists' own behavioural errors, with reported shares ranging from 36% to 59% [43–47]. Moreover, Rella Riccardi et al. [48] showed that pedestrians who cross outside designated facilities face an 18% higher risk of fatal injury compared with non-fatal outcomes. In response to this evidence, Serbian authorities introduced monitoring of pedestrian-related RSPIs in 2017, including indicators of legal crossing behaviour, distraction and children's behaviour. However, because these measures have been collected for a relatively short period, they could not be included in the present analysis.

For motorised two-wheelers, only speed-related RSPI in urban areas showed a statistically significant association with crash outcomes. This result is in line with earlier studies identifying vehicle speed as a key contributing factor in crashes involving motorised two-wheelers [49, 50]. For example, Jones et al. [51] reported that approximately one-third of fatal motorcycle crashes were related to speeding, which supports the relevance of the observed association in the Serbian context.

Higher values of the RSPI related to protective systems were also associated with fewer passenger-car occupant casualties. This result corroborates the well-established protective effect of seat belt use in reducing injury severity and fatal outcomes among vehicle occupants [52, 53]. In addition, indicators capturing the rate of speeding exceedances in urban areas showed a significant association with the number of injured passenger-car occupants. Taken together, these findings suggest that PAUs with higher levels of in-vehicle protective system use and lower rates of urban speeding tend to experience less severe occupant-related outcomes.

Finally, when examining the relationship between RSPI and children's injuries, the strongest associations were again observed for indicators related to protective systems. In particular, the use of child restraint systems among children aged 4–12 years showed a more pronounced effect, which may be explained by the substantial increase in this RSPI over the observed period. This result is consistent with numerous previous studies emphasising the critical role of child restraint systems in improving child safety in traffic [54–56]. At the same time, the unexpected association observed for distraction-related RSPI and children's injuries highlights an area that requires further investigation and more refined measurement approaches.

## 5. CONCLUSIONS

This study provides one of the first long-term analyses of the relationship between RSPI and traffic crash outcomes in Serbia. By combining RSPI monitoring with fixed-effects and Mundlak correlated random-effects models for panel data, this study provides robust empirical evidence on the links between safety performance and crash outcomes. Based on the conducted research, the following key conclusions can be emphasised:

- Improving the use of protection systems and improving RSPI related to urban speed showed a significant relationship with the reduction of the outcomes of traffic crashes. Such results indicate that these two groups of indicators have the greatest potential for improving road safety in local entities. Speed management on the local road network is becoming an increasing challenge and requires growing resources. The group of protective system indicators traditionally has the greatest importance for road safety in most of the analysed European regions [15, 17, 18].
- RSPI related to speed in rural areas, and distraction has not shown a connection with the outcomes of traffic crashes. On rural roads, traffic conditions at higher speeds prevail, under which traffic can be conducted safely, provided that there are no additional driver errors that would lead to hazardous situations. Therefore, speed on rural roads does not show an association with the consequences of traffic crashes to the same extent as it does in urban areas.
- RSPI related to powered two-wheelers, unexpected effects on the behaviour of powered two-wheelers, because of the small share of powered two-wheelers in Serbia. Namely, powered two-wheelers account for only 3.6% of vehicles in the Serbian vehicle fleet [57]. Therefore, RSPI related to powered two-wheelers does not show a significant impact on the overall consequences of traffic crashes in Serbia.

These findings align with evidence from other European countries, but also highlight context-specific challenges in Serbia. The most important experiences during the ten-year measurement of RSPI in Serbia indicate that it is necessary to implement the following activities:

- Establishing/continuing measurement of RSPI related to protective systems and speed;
- Development of a methodology for determining speed measurement locations (e.g. based on historical traffic crash data);
- More detailed observation of RSPI related to distraction (observe other activities while driving);
- Monitoring of RSPI related to vulnerable road users (behaviour of pedestrians and cyclists).

These activities will enable decision-makers with more accurate insights into road users' behaviour, enabling benchmarking activities at local and national levels. Based on that, decision-makers will be able to make quality decisions in order to achieve road safety goals. Specifically, local authorities should use RSPI within their strategic documents as a measure for monitoring the state of road safety.

In this research, we noted certain limitations. One of the reasons why the speed-related RSPI showed little impact could be the interruption of measurement continuity in 2020. The reason for this interruption was the problems caused by the COVID-19 pandemic. In addition, an additional limitation is the fact that specific RSPI could not be research subjects due to the short period of collection (e.g. RSPI related to pedestrian behaviour, vehicles, roads, etc.).

Future studies should examine the influence of RSPIs while accounting for additional contextual characteristics of police administration units (PAUs), such as socio-demographic and economic profiles, road infrastructure attributes and emergency medical service availability, using extended panel and/or multilevel modelling frameworks. Moreover, crash consequences should be analysed in greater detail through disaggregated outcomes by road user group, crash type and contributory factors, consistent with the CADA structure. As emerging modes gain relevance, indicators for new participant categories – particularly micromobility – should be defined and systematically monitored to better capture exposure and safety risks. These extensions would enable a clearer separation of short-term behavioural changes from long-term structural differences between PAUs in road safety performance. Finally, future research would benefit from

stronger institutional coordination and data integration, which would facilitate the inclusion of additional RSPI domains (e.g. alcohol involvement, vehicle safety standards and road infrastructure safety).

Strengthening RSPI monitoring and linking it to decision-making at local and national levels will be essential for Serbia to achieve its 2030 road safety targets and contribute to global goals such as Vision Zero, serving as a good example for other countries in transition.

## DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## DECLARATION OF GENERATIVE AI IN SCIENTIFIC WRITING

During the preparation of this work, the authors did not use generative artificial intelligence (AI) and AI-assisted technologies in the writing process.

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