

ANALYSIS OF SAFETY IMPACT OF PAVED SHOULDER WIDTH ON CZECH SECONDARY ROADS

Jiří AMBROS¹, Zuzana KŘIVÁNKOVÁ², Robert ZŮVALA³, Kateřina BUCSUHÁZY⁴, Jindřich FRÍČ⁵

^{1, 2, 3, 4, 5} CDV – Transport Research Centre, Brno, Czech Republic

Abstract:

Traffic safety is influenced, among other factors, by characteristics of the roads, which include the width of the shoulder. Shoulder width was noted to have a large effect on crash frequency, as well as on traffic speed. In this paper, we focused on paved shoulders. Previous studies confirmed that increasing the width of the paved shoulder is associated with a decrease in crash frequency. However, wider shoulders may encourage higher driving speed, which is related to an increase of impact speed and crash severity – this issue was hypothesized, but not statistically investigated. Thus, conclusions based on crashes and speeds contradict each other, and there is no simple answer to the question of the safety impact of wide shoulders. To address this gap, we analyzed a sample of two most typical categories of Czech secondary roads, which differ only in the paved shoulder width (S9.5 roads with 0.75m-wide shoulder, and S11.5 roads with 1.75m-wide shoulder) and thus present a suitable example for studying the safety impact of paved shoulder width. We used generalized linear models of crash frequency, and multinomial logistic models of crash severity (separately for single-vehicle and multi-vehicle crashes), as well as a statistical test of differences in speed for the two road categories.

The results showed that: Firstly, there were fewer crashes on S11.5 roads compared to S9.5 roads; this was true for both single-vehicle and multi-vehicle crashes. Secondly, single-vehicle crashes on S11.5 roads were more severe compared to S9.5 roads; the change of severity in multi-vehicle crashes was not statistically significant. Thirdly, driving speeds on S11.5 roads were approx. by 7 km/h higher compared to S9.5 roads. These findings support the hypothesis of an association between wider shoulders, higher speeds, and increased crash severity, especially in the case of single-vehicle crashes. As a practical solution, various speed management measures, including widening to a 2+1 road, may be recommended.

Keywords: paved shoulder, shoulder width, safety, crash, speed, secondary road

To cite this article:

Ambros, J., Krivanková, Z., Zůvala, R., Bucsuházy, K., Frič J., 2021. Analysis of safety impact of paved shoulder width on Czech secondary roads. *Archives of Transport*, 60(4), 125-136. DOI: <https://doi.org/10.5604/01.3001.0015.6148>



Contact:

1) jiri.ambros@cdv.cz [<https://orcid.org/0000-0003-2707-6243>] – corresponding author; 2) zuzana.krivankova@cdv.cz [<https://orcid.org/0000-0002-4691-070X>]; 3) robert.zuvala@cdv.cz [<https://orcid.org/0000-0003-2038-7292>]; 4) katerina.bucsuhazi@cdv.cz [<https://orcid.org/0000-0003-1247-6148>]; 5) jindrich.fric@cdv.cz [<https://orcid.org/0000-0002-8820-378X>]

1. Introduction

Traffic safety is influenced, among other factors, by the characteristics of the roads. In terms of crash causes, road environment has been attributed to approximately 30% of crashes – this proportion was confirmed by a series of in-depth investigations since the 1970s, and is still valid until today (Shinar, 2017). Road characteristics include cross-section parameters, which have been identified as safety-related by several reviews (Babkov, 1975; Hedman, 1990; Ruyters et al., 1994; Ogden, 1997; Lamm et al., 1999; Wang et al., 2013; Andres et al., 2015; Gaca and Pogodzińska, 2017; Papadimitriou et al., 2019).

This study focuses specifically on shoulder width. According to *Highway Safety Manual* (AASHTO, 2010), the shoulder is a portion of the road for the accommodation of stopped vehicles, emergency use, or other users. In principle, it may be either paved or unpaved. In this paper, we considered paved shoulders only.

Shoulder width has an important role. In the Transportation Research Board's synthesis of knowledge regarding the key design elements, known as controlling criteria (Harwood et al., 2014), the shoulder width was noted to have the largest effect on the crash frequency of any of the controlling criteria for rural roads, as well as the largest effect on traffic speed of any of the controlling criteria for rural two-lane roads.

Roads may have different shoulder widths. In terms of their safety impacts, several international reviews reported evident safety benefits. For example, according to the meta-analysis in the renowned *Handbook of Road Safety Measures* (Elvik et al., 2009, pp. 222–223):

- “Increasing shoulder width has been found to reduce the number of accidents, mostly injury accidents.”
- “The majority of studies have found significantly fewer accidents on roads with wider shoulders.”
- “It can be concluded that wider shoulders almost always result in fewer accidents.”

However, this information only relates to crash frequency and does not reflect crash severity. At the same time, several studies and reviews (Martens et al., 1997; Ivan et al., 2009; TRB, 2011; Gitelman et al., 2016) mentioned that increasing shoulder width provides extra driving space and a sense of security which is associated with increased driving speed.

Since higher driving speed is clearly related to increased occurrence and severity of crashes (OECD, 2018), some authors (Hauer, 2000; Stamatiadis et al., 2009; Usami, 2017) indicated the possibility that the same association holds for increasing shoulder width. However, it was not confirmed statistically, probably due to the limited availability of network-wide speed data.

To sum up, there is no simple answer to the question of the safety impact of wide shoulders. In fact, conclusions based on crashes and speeds contradict each other: while the former sees widening shoulders as a crash-reduction measure, the latter sees it as a way towards increasing crash severity. With this uncertainty, roads with wider shoulders are still commonly preferred in practice, with a goal of improving road capacity, and without considering their possible contribution to higher speed and increased crash severity. This specific state-of-practice exists also in Czechia, which motivated us to investigate safety impacts of paved shoulder width in Czechia in terms of crash frequency, severity, and speed.

Following Section 2 summarizes previous studies of the safety impact of shoulder width on secondary roads and emphasizes the added value of our study. Next, Data and methods (Section 3), Results (Section 4), Summary and discussion (Section 5), and Conclusions (Section 6) are presented.

2. Previous studies of the safety impact of shoulder width on secondary roads

Secondary roads are usually the most critical category, when compared to safety levels of motorways or expressways (OECD, 1999; Gatti et al., 2007). In Czechia, the two most typical secondary road categories (labeled as S9.5 and S11.5) both have 3.5m-wide lanes. To improve traffic capacity, the latter category has wider paved shoulders. Since their only physical difference is in the paved shoulder width (0.75m-wide on S9.5 roads, and 1.75m-wide on S11.5 roads), they are a suitable example for studying the safety impact of paved shoulder width. Some previous Czech studies attempted this comparison using crash rates or crash density, but their findings were mixed: while Kafaňková and Andres (2008) concluded that S11.5 roads were safer, Ambros (2011) found the opposite in the case of standard traffic volumes (below design traffic volume); on the other hand, in case of higher traffic volumes

(above design traffic volume) S11.5 roads were safer than S9.5 roads.

In terms of methodology, most of the international studies, which focused on the safety impact of shoulder width, were based on a cross-sectional comparison (i.e., regression models); only a few used before-after design (see reviews by Zegeer and Perkins, 1980; Hauer, 2000; Elvik et al., 2009; Usami, 2017). Some studies applied case-control study design (Gross et al., 2009; Gross and Donnell, 2011; Gitelman et al., 2019); it was nevertheless concluded that when comparing cross-sectional and case-control methods, the final effect of the shoulder width was similar (Gross and Donnell, 2011). Some studies also analyzed the joint safety effect of lane and shoulder width (Gross et al., 2009; Labi et al., 2017; Pokorný et al., 2020); but since lane width is kept constant on both S9.5 and S11.5 roads, we have not adopted such analysis design.

Nevertheless, the majority of existing safety impact studies (including the mentioned Czech analyses) focused only on crash frequency; as also confirmed by Haghghi et al. (2018), very few have investigated the influence on the crash injury severity outcome. This is why we decided to study the safety impact in terms of both crash frequency and crash severity. To investigate the previously hypothesized (but not confirmed) relationship to driving speed, we used also speed data. Compared to previous studies, the simultaneous consideration of all these elements is a novelty of the presented study.

3. Data and methods

We focused on a sample of rural undivided segments of Czech national road categories S9.5 and S11.5, which are physically different only in the width of the paved shoulder. Scheme and photos are provided in Fig. 1.



Fig. 1. Scheme of road categories S9.5 and S11.5 with illustrative photographs (adapted from Mapy.cz)

The segments were defined, based on their horizontal alignment, as tangents (straight sections) and curves of varying length. While several alternative approaches to road network segmentation exist, the approaches based on tangents and curves were identified as superior to several others (Cafiso et al., 2018; Ghadi and Török, 2019). To ensure representativeness of speeds, we discarded all segments, which included potential speed influencers, such as intersections, pedestrian crossings, bus stops, tunnels, railway level crossings, or traffic calming measures. This selection should also limit the effect of uncontrolled confounding factors (e.g., minor road traffic volumes, number of crossing pedestrians) and thus increase homogeneity with respect to safety performance.

The sample of tangents and curves originated from a previous project, which focused on the speed and safety performance of national roads (Ambros et al., 2017). The added benefit was the availability of speeds calculated from GPS data of company probe vehicles (also known as “floating car data”, FCD; Ambros et al., 2019, 2020). FCD was collected over eight months (October 2014 to May 2015) and used to statistically estimate the 85th percentile of free-flow speed. Only segments with at least 100 probe drives were used. The representativeness of FCD-based speed was compared with spot speed from a statistical radar SierzegaSR4: FCD-based speed was on average 2 km/h higher than the radar speed, which was deemed as acceptable difference, compared to other studies that reported differences up to 16 km/h (Ambros et al., 2021). More information on segmentation and speed data, used in this paper, is available in Ambros et al. (2017).

Although we planned to use original direction-specific speeds, assigning crashes to individual driving directions turned out to be quite uncertain. In addition, head-on crashes in principle cannot be assigned to a single direction. Thus, we decided to analyze a segment level, using averaged speed from both directions (where available).

We assigned five years of crash data (2015–2019) to the segments. Following previous studies (e.g., Gitelman et al., 2019) and crash frequency modeling recommendations (e.g., Geedipally and Lord, 2010; Høyevoll and Hesjevoll, 2020), we distinguished single- and multi-vehicle crashes (SV and MV) and excluded vehicle-pedestrian crashes, which presented

less than 1% of crashes. The proportion was approx. 60% and 40% of SV and MV crashes, respectively. Following analyses were conducted in IBM SPSS Statistics 20. The further text describes data and methods in three individual analyses: crash frequency analysis, crash severity analysis, speed analysis.

In total, we used 568 segments, with an average length of 0.25 km and a total length of approx. 143 km. In terms of length, the sample represents 3% of rural segments of the Czech national road network. On the analyzed segments average traffic volume (AADT) based on the latest national traffic census was around 9100 veh/day. Road categories S9.5 and S11.5 had approximate shares of 38% and 62%, respectively.

There were 548 crashes in total. For the crash frequency analysis, we originally planned to distinguish four levels of crash severity (in decreasing order): fatal crash, serious injury crash, slight injury crash, property damage only (PDO) crash. However, frequencies of fatal, serious, and slight crashes on the analyzed segments were very low. Therefore, we could only distinguish injury crashes (sum of fatal + serious + slight injury crashes) and total crashes, while the share of injury crashes was approx. 47%. Descriptive characteristics, related to S9.5 and S11.5 road categories, are listed in Table 1.

We developed generalized linear models (GLMs) with crash frequency as the response variable, and exposure (AADT and length), and road category as explanatory variables.

GLMs were developed separately for crash types (SV and MV crashes) and crash severities (total or injury crashes). Consistently with state-of-the-art (Reurings et al., 2005; Lord and Mannering, 2010; Yannis et al., 2017; Ambros et al., 2018), models were developed with negative binomial error structure and logarithmic link function. This means that in linearized form the exposure variables (AADT and length) were input as logarithms:

$$\ln(N) = \beta_0 + \beta_1 \cdot \ln(L\text{EN}) + \beta_2 \cdot \ln(\text{AADT}) + \beta_3 \cdot \text{CAT} \quad (1)$$

where: N is crash frequency, LEN is segment length, $AADT$ is annual average daily traffic volume, β_0 and β_i ($i = 1, 2, 3$) are regression constant (intercept) and coefficients, respectively, to be estimated in modeling.

Crash severity analysis was conducted on segments where the crash occurred, which entailed 254 segments with 548 crashes. In this analysis, we distinguished three levels of crash severity (1 – slight injury, 2 – serious injury, 3 – fatal injury). The overview of crash severity levels, related to SV and MV crash types and S9.5 and S11.5 road categories, is provided in Table 2.

We developed multinomial logistic models (MLMs) with crash severity as the response variable with three levels of maximum severity (1 – slight injury, 2 – serious injury, 3 – fatal injury), and road category as an explanatory variable. MLMs were developed separately for SV and MV crash types.

In addition, we analyzed and statistically tested differences in speed for two road categories using the Mann-Whitney *U* test for non-normally distributed variables.

4. Results

4.1. Crash frequency analysis

We attempted to develop four GLMs, based on their response variable (crash frequency):

- *SV_inj* ... frequency of single-vehicle crashes (injury crashes)
- *SV_total* ... frequency of single-vehicle crashes (total crashes)
- *MV_inj* ... frequency of multi-vehicle crashes (injury crashes)

- *MV_total* ... frequency of multi-vehicle crashes (total crashes)

The goal was to obtain models, where explanatory variables will have statistically significant effects on at least 95% level ($p \leq 0.05$). However, models with injury crash frequency (*SV_inj* and *MV_inj*) did not meet this criterion. Parameters of successful models of total crash frequency (*SV_total* and *MV_total*) are reported in Table 3.

Signs of regression coefficients β enable interpreting directions of influence of individual variables on response variable:

- *Positive* relationship means that a change of a variable is associated with a change of response variable in the same direction. Therefore, increasing variable increases crash frequency, and decreasing variable decreases crash frequency.
- *Negative* relationship that a change of a variable is associated with a change of response variable in the opposite direction. Therefore, increasing variable decreases crash frequency, and decreasing variable increases crash frequency.

The signs of exposure variables were positive as expected, which means that with increasing AADT and lengths also crash frequency increases. The negative sign of road category indicates that crash frequency on S11.5 roads was lower compared to S9.5 roads.

Table 1. Descriptive characteristics of the road, speed, and crash data

	S9.5 roads				S11.5 roads			
	Min.	Max.	Mean	Std. Dev.	Min.	Max.	Mean	Std. Dev.
Length [km]	0.01	2.53	0.25	0.34	0.01	2.81	0.25	0.31
AADT [veh/day]	3893	17,072	8719.93	2733.50	3889	29,950	9386.23	3138.90
Speed [km/h]	37	123	87.71	12.60	50	119	94.53	7.66
5-year crash frequencies								
- total crashes	0	13	1.12	1.95	0	11	0.87	1.49
- injury crashes	0	8	0.43	1.08	0	10	0.29	0.90

Table 2. Overview of crash severity levels

	Single-vehicle crashes (SV)				Multi-vehicle crashes (MV)			
	S9.5 roads		S11.5 roads		S9.5 roads		S11.5 roads	
	Count	%	Count	%	Count	%	Count	%
Total	147	100.0%	182	100.0%	94	100.0%	125	100.0%
No injury	88	59.9%	107	58.8%	37	39.4%	60	48.0%
Slight injury	45	30.6%	69	37.9%	34	36.2%	45	36.0%
Serious injury	10	6.8%	5	2.7%	10	10.6%	10	8.0%
Fatal injury	4	2.7%	1	0.5%	13	13.8%	10	8.0%

Table 3. Parameters of generalized linear models

	<i>SV total model</i>		<i>MV total model</i>	
	β	Sig.	β	Sig.
Intercept	-6.271	0.002	-7.685	0.000
ln(<i>LEN</i>)	0.841	0.000	0.776	0.000
ln(<i>AADT</i>)	0.785	0.000	0.881	0.000
Road category S11.5*	-0.357	0.012	-0.273	0.049

*Note: The coefficient is to be interpreted in comparison to the reference category S9.5 with zero coefficient.

4.2. Crash severity analysis

We attempted to develop multinomial logistic models (MLMs) separately for single- and multi-vehicle crashes (SV and MV). The goal was to obtain a model with an overall statistically significant effect on at least 95% level ($p \leq 0.05$). However, the model for MV crashes did not meet this criterion. Parameters of the successful model for SV crashes ($p = 0.033$) are reported in Table 4.

Table 4. Parameters of the multinomial logistic model

Severity level*	Variables	β
1 (slight injury)	(Intercept)	2.420
	Road category S11.5**	1.814
2 (serious injury)	(Intercept)	0.916
	Road category S11.5**	0.693

Notes:

* The coefficients are to be interpreted in comparison to the reference level 3 (fatal).

** The coefficient is to be interpreted in comparison to the reference category S9.5 with zero coefficient.

Again, signs of regression coefficients β enable interpreting the direction of influence of explanatory variable on a response variable. For both severity levels, the sign for road category S11.5 is positive, which indicates higher severity compared to road category S9.5.

4.3. Speed analysis

In this analysis, speeds for road categories S9.5 and S11.5 were compared. With exception of two outliers below 50 km/h, all speeds from all 568 road segments were used. Mean speeds are listed in Table 5 – the difference was approx. 6.7 km/h. Next, Fig. 2 shows box plots for both road categories.

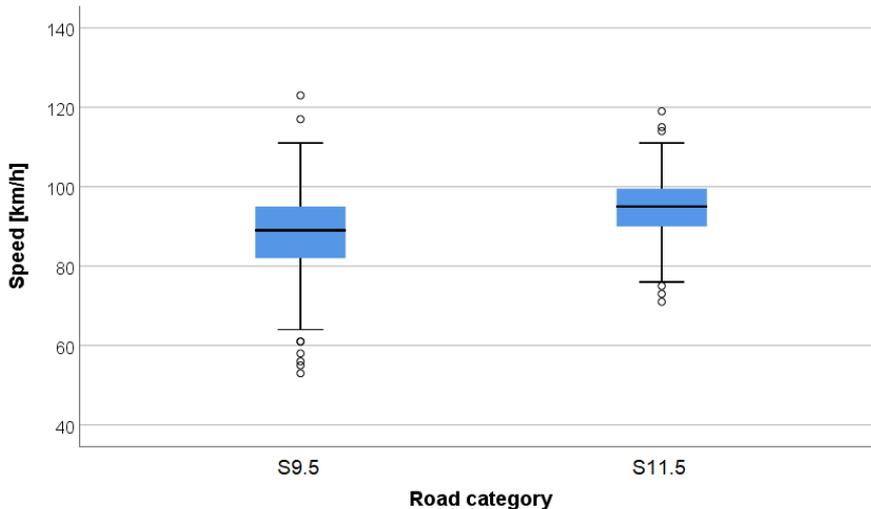


Fig. 2. Box plots of speeds in road categories S9.5 and S11.5

Table 5. Mean speeds for road categories S9.5 and S11.5

Road category	<i>n</i>	Mean speed
S9.5	214	87.95 km/h
S11.5	352	94.66 km/h

We statistically tested differences in speed for the two road categories using the Mann-Whitney *U* test for non-normally distributed variables. Based on the test results, speeds in the road category S11.5 are significantly higher than in the road category S9.5 ($U = 23,769.0$; $p < 0.001$).

5. Summary and discussion

To address the current uncertainty regarding the safety impact of paved shoulder width, we investigated its impacts in Czech conditions in terms of crash frequency, severity, and speed. Analyzing the data from road segments of two categories (S9.5 roads with 0.75m-wide shoulder, and S11.5 roads with 1.75m-wide shoulder) we found that:

- 1) There were fewer crashes on S11.5 roads compared to S9.5 roads. This was true for both single-vehicle (SV) and multi-vehicle (MV) crashes.
- 2) However, SV crashes on S11.5 roads were more severe compared to S9.5 roads. (Change of severity in MV crashes was not statistically significant.)
- 3) Driving speeds on S11.5 roads were approx. by 7 km/h higher compared to S9.5 roads.

These findings seem to support the previously hypothesized relationship between crash frequency, severity, and speed (Hauer, 2000; Stamatidis et al., 2009; Usami, 2017): it is likely that while wider shoulders on S11.5 roads provide extra driving space (hence lower crash frequency), this safety buffer may lead to a sense of security and thus encourage higher speed, which in turn increases impact speed and crash severity.

The second finding merits some discussion: why the increase of severity on S11.5 roads compared to S9.5 roads was found in SV crashes, and not in MV crashes? As previously mentioned, we developed separate models for these crash types, since it is known that there are several differences in the causation of SV and MV crashes (e.g., Martensen and Dupont, 2013; Høye and Hesjevoll, 2020). The following examples illustrate the possible differences

and their implications on crash severity comparisons:

- Relative frequency of injury crashes (from Table 2) is higher in the two most frequent types of SV crashes: fixed-object crashes and run-off-road crashes, with visible differences in proportions of run-off-road crashes on S9.5 roads and fixed-object crashes on S11.5 roads (see Fig. 3). Since generally, fixed-object collisions are more severe than run-off-road crashes (Reed and Morris, 2012; Jurewicz et al., 2014; Hermitte, 2017), the increase in the latter category may explain the higher severity of SV crashes on S11.5 roads.
- According to the most frequent contributory factors (Elgner, 2020), obtained from the Czech In-Depth Accident Study (CzIDAS; Zůvala et al., 2021), there are differences between SV and MV crashes: while excessive and inappropriate speed (in short “speeding”) is the most prevalent in SV crashes, inattention is listed as the most frequent in MV crashes (see Fig. 4).

To sum up, both SV and MV crashes involve several collision types, and each of them may have a different relationship to crash frequency and severity. Nevertheless, SV crashes are more related to speeding and thus increased severity, in contrast to MV crashes.

When thinking about the generalization or transferability of our findings, some points need to be noted:

- The sample represented only 3% of the length of rural segments of Czech national roads, mainly due to the limited availability of speed data. Another reason may be that we were quite strict in segmentation (excluding segments with potential speed influencers), as mentioned in Section 3.
- Regarding relationships between speed and crash severity (i.e., fatality and injury risks), the general experience is accumulated mainly from in-depth crash investigations, using impact speeds, either from crash reconstructions or event data recorders (e.g., Bucsuházy et al., 2018; Doecke et al., 2020). In addition, most attention was given to vehicle-pedestrian crashes (for a review, see Hussain et al., 2019). In contrast, our study is based on driving speed, which is linked to pre-crash or impact speeds, but the exact form of relationship is not known (Jurewicz et al., 2016; Fitzharris et al., 2020). Nevertheless, several authors used similar speed data when analyzing injury risk (e.g., Gårder, 2004; Krøyer, 2015).

- In the international context, shoulders are often much wider than 0.75m or 1.75m in our sample: for example, in Australia shoulder width may be up to 3 m (Fanning et al., 2016); in Israel, common shoulder width is 3 m (Bassan et al., 2015); and on US two-lane roads shoulder may be as wide as 12 feet which equals 3.7 m (AASHTO, 2010). In addition, some authors indicated a “breaking point” between 2m and 3mpaved shoulder width, where crash risk changes from increasing to decreasing trend (Hedman, 1990; Ogden, 1997). Gitelman et al. (2019) hypothesized that this change of trend may reflect a difference in opportunities to stop or

park the vehicle on the shoulder; however, this was probably not the case in our sample, where the proportion of collisions with stopped or parked vehicles was almost identical on both S9.5 and S11.5 roads (see Fig. 3).

In addition, we cannot rule out the possibility that different segmentation would lead to different results of crash frequency and crash severity modeling. We are also aware that estimation of FCD-speeds included several ambiguous steps, where the selection of other alternatives may influence the final results.

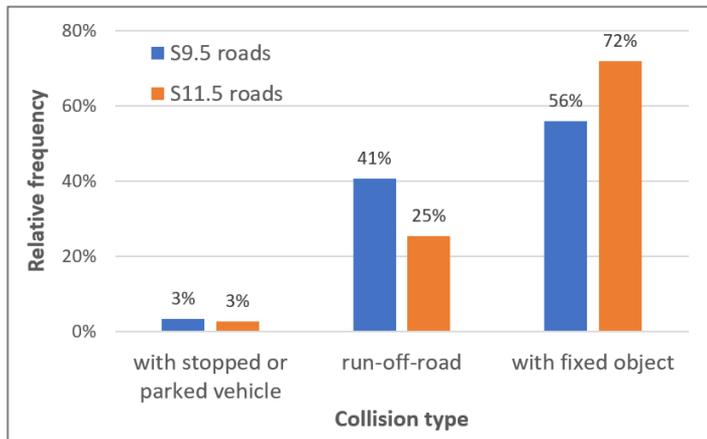


Fig. 3. Relative frequency of single-vehicle injury crashes according to road and collision types

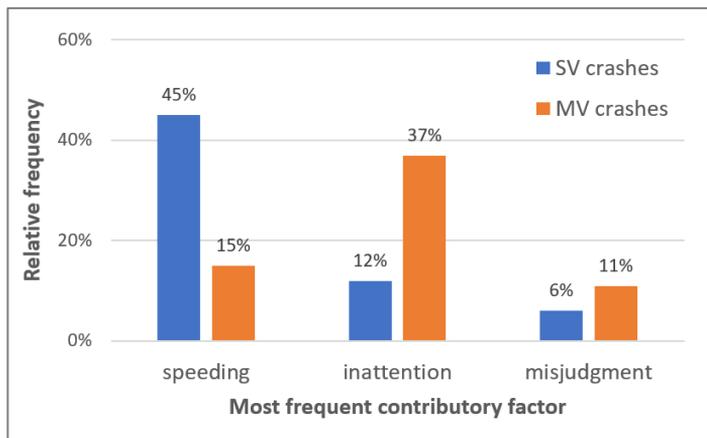


Fig. 4. Relative frequency of the most frequent crash contributory factors

In terms of further research, a larger sample of road segments (and crashes) would be beneficial and may also enable analyzing the influence of other variables, for example, characteristics of cross-section, alignment consistency, or road surroundings. Having more information on driving behavior or pre-crash conditions, as well as the relationship between driving speed and impact speed, would be also valuable; however, the approaches to the collection of such data, such as in-depth crash investigations or naturalistic driving studies, have limited coverage in practice.

6. Conclusions

A number of previous studies confirmed that increasing the width of the paved shoulder is beneficially associated with a decrease in crash frequency. However, at the same time, wider shoulders may encourage higher driving speed, which in turn increases impact speed and crash severity – this issue was hypothesized, but not statistically investigated. To address this gap, we analyzed a sample of the two most typical categories of Czech secondary roads (labeled as S9.5 and S11.5), which differ only in the paved shoulder width (0.75m-wide on S9.5 roads, and 1.75m-wide on S11.5 roads) and is thus a suitable example for studying the safety impact of paved shoulder width. Our findings, based on simultaneous availability of crash frequency, crash severity, and speed data, supported the hypothesis of an association between wider shoulders, higher speeds, and increased crash severity, especially in the case of single-vehicle crashes.

Therefore, roads with wider shoulders provide an increase in traffic capacity, but at the cost of more severe crashes. What is the way out of this paradox? Based on the identified relationship to speed, the various measures of speed management may be applied, including traffic signs, enforcement, campaigns, etc. (OECD, 2006). Another option is using the concept of self-explaining roads, which includes redesigning (widening) the S11.5 roads to continuous three-lane cross-section with alternating passing lanes, known as “2+1” road. This design alternative has been known internationally for around two decades and showed significant operational improvements; safety benefits have been also substantial, especially when combined with median barriers (for a summary, see TRB, 2003). More recently the con-

cept was introduced also in Czech technical guidelines (Radimský et al., 2014), labeled as S13.5. An update of the Czech road design standard (ÚNMZ, 2018) stated that the current S11.5 cross-section may (in justified circumstances) be redesigned to S13.5; several projects are currently underway. As we learned from local experts (Ambros, 2019), two neighboring countries of Czechia (Austria and Poland) already stopped designing roads with wide shoulders and adopt a 2+1 cross-section as the only alternative. In general, Czech stakeholders accept this fact as well; however, a number of S11.5 road projects remain in their original cross-section. In the future, it may be interesting to evaluate the safety impacts of 2+1 (S13.5) roads and compare them with current S11.5 roads.

Acknowledgments

The paper was produced with the financial support of the Ministry of Transport within the program of the long-term conceptual development of research organizations.

References

- [1] AASHTO (2010). *Highway Safety Manual. First Edition*. Washington: American Association of State Highway and Transportation Officials (AASHTO).
- [2] Ambros, J. (2011). *Relationship between road width and safety*. Young Researchers Seminar 2011, Copenhagen.
- [3] Ambros, J., Valentová, V., Gogolín, O., Andrášik, R., Kubeček, J., & Bíl, M. (2017). Improving the Self-Explaining Performance of Czech National Roads. *Transportation Research Record*, 2635, 62–70.
- [4] Ambros, J., Jurewicz, C., Turner, S., & Kieć, M. (2018). An international review of challenges and opportunities in development and use of crash prediction models. *European Transport Research Review*, 10, 35.
- [5] Ambros, J. (2019). *Rešerše podkladů k porovnání kategorií dvoupruhových silnic S 9,5 a S 11,5*. Unpublished contract report. Brno: CDV – Transport Research Centre.
- [6] Ambros, J., Altmann, J., Jurewicz, C., & Chevalier, A. (2019). Proactive assessment of road curve safety using floating car data: An exploratory study. *Archives of Transport*, 50(2), 7–15.

- [7] Ambros, J., Elgner, J., Turek, R., & Valentová, V. (2020). Where and when do drivers speed? A feasibility study of using probe vehicle data for speeding analysis. *Archives of Transport, 53(1)*, 103–113.
- [8] Ambros, J., Jurewicz, C., Chevalier, A., & Valentová, V. (2021). Speed-Related Surrogate Measures of Road Safety Based on Floating Car Data. In Macioszek, E., & Sierpiński, G. (Eds.), *Research Methods in Modern Urban Transportation Systems and Networks* (pp. 129–144). Cham: Springer Nature Switzerland AG.
- [9] Andres, J., Mikulík, J., Frič, J., Kafaňková, J., Růcker, J., Motl, J., Kratochvílová, S., Tvarožková, L., Kaniová, K., Plánka, L., Krtička, M., Běreš, V., Zůvala, R., & Tecl, J. (2015). *Hloubková analýza dopravních nehod*. Brno: CDV – Transport Research Centre.
- [10] Babkov, V.F. (1975). *Road conditions and traffic safety*. Moscow: Mir.
- [11] Bassan, S., Zilbershtein, R., & Frischer, B. (2015). *Country Report: Israel*. 5th International Symposium on Highway Geometric Design, Vancouver.
- [12] Bucsuházy, K., Zůvala, R., Doecke, S., & Ambros, J. (2018). *Investigation of pre-crash vehicle speed*. Fourth International Conference on Traffic and Transport Engineering, Belgrade, 773–779.
- [13] Cafiso, S., D'Agostino, C., & Persaud, B. (2018). Investigating the influence of segmentation in estimating safety performance functions for roadway sections. *Journal of Traffic and Transportation Engineering (English Edition), 5*, 129–136.
- [14] Doecke, S.D., Baldock, M.R.J., Kloeden, C.N., & Dutschke, J.K. (2020). Impact speed and the risk of serious injury in vehicle crashes. *Accident Analysis and Prevention, 144*, 105629.
- [15] Elgner, J. *Statistické analýzy – řidiči osobních vozidel*. Ministry of Transport, Prague. Retrieved from <https://www.ibesip.cz/Statistiky/Statistiky-nehodovosti-v-Ceske-republice/Statisticke-analyzy/Ridici-osobnich-vozidel> on June 7, 2021.
- [16] Elvik, R., Høye, A., Vaa, T., & Sørensen, M. (2009). *The Handbook of Road Safety Measures. Second Edition*. Bingley: Emerald.
- [17] Fanning, R., Veith, G., Whitehead, M., & Aumann, P. (2016). *Guide to Road Design Part 3: Geometric Design*. Publication AGRD03-16. Sydney: Austroads.
- [18] Fitzharris, M., Lenné, M. G., Corben, B., Pok Arundell, T., Peiris, S., Liu, S., Stephens, A., Fitzgerald, M., Judson, R., Bowman, D., Gabler, C., Morris, A., & Tingvall, C. (2020). *Enhanced Crash Investigation Study (ECIS) Report 1: Overview and Analysis of Crash Types, Injury Outcomes and Contributing Factors*. Melbourne: Monash University.
- [19] Gaca, S., & Pogodzińska, S. (2017). Speed management as a measure to improve road safety on Polish regional roads. *Archives of Transport, 43(3)*, 29–42.
- [20] Gårder, P. E. (2004). The impact of speed and other variables on pedestrian safety in Maine. *Accident Analysis and Prevention, 36*, 533–542.
- [21] Gatti, G., Polidori, C., Galvez, I., Mallschützke, K., Jorna, R., van de Leur, M., Dietze, M., Ebersbach, D., Lippold, C., Schlag, B., Weller, G., Wyczynski, A., Iman, F., & Aydin, C. (2007). *Safety Handbook for Secondary Roads*. RIPCORDER-ISEREST project deliverable 13.
- [22] Geedipally, S.R., & Lord, D. (2010). Investigating the effect of modeling single-vehicle and multi-vehicle crashes separately on confidence intervals of Poisson-gamma models. *Accident Analysis and Prevention, 42*, 1273–1282.
- [23] Ghadi, M., & Török, Á. (2019). Comparison of different road segmentation methods. *Promet – Traffic & Transportation, 31*, 163–172.
- [24] Gitelman, V., Pesahov, F., Carmel, R., & Bekhor, S. (2016). The identification of infrastructure characteristics influencing travel speeds on single-carriageway roads to promote self-explaining roads. *Transportation Research Procedia, 14*, 4160–4169.
- [25] Gitelman, V., Doveh, E., Carmel, R., & Hakkert, S. (2019). The influence of shoulder characteristics on the safety level of two-lane roads: A case-study. *Accident Analysis and Prevention, 122*, 108–118.
- [26] Gross, F., Jovanis, P. P., & Eccles, K. (2009). Safety Effectiveness of Lane and Shoulder

- Width Combinations on Rural, Two-Lane, Un-divided Roads. *Transportation Research Record*, 2103, 42–49.
- [27] Gross, F., & Donnell, E.T. (2011). Case-control and cross-sectional methods for estimating crash modification factors: Comparisons from roadway lighting and lane and shoulder width safety effect studies. *Journal of Safety Research*, 42, 117–129.
- [28] Haghighi, N., Liu, X.C., Zhang, G., & Porter, R.J. (2018). Impact of roadway geometric features on crash severity on rural two-lane highways. *Accident Analysis and Prevention*, 111, 34–42.
- [29] Harwood, D.W., Hutton, J.M., Fees, C., Bauer, K.M., Glen, A., & Ouren, H. (2014). *Evaluation of the 13 Controlling Criteria for Geometric Design*. NCHRP Report 783. Washington: Transportation Research Board.
- [30] Hauer, E. (2000). *Shoulder Width, Shoulder Paving and Safety*. Retrieved from www.RoadSafetyResearch.com on September 13, 2007.
- [31] Hedman, K.O. (1990). *Road design and safety*. Proceedings of Strategic Highway Research Program and Traffic Safety on Two Continents, Gothenburg, 226–238.
- [32] Hermitte, T. (2017). *SafetyCube scenarios – Single vehicle accident*. Retrieved from www.RoadSafety-DSS.eu on June 24, 2020.
- [33] Høyе, A.K., & Hesjevoll, I. S. (2020). Traffic volume and crashes and how crash and road characteristics affect their relationship – A meta-analysis. *Accident Analysis and Prevention*, 145, 105668.
- [34] Hussain, Q., Feng, H., Grzebieta, R., Brijs, T., & Olivier, J. (2019). The relationship between impact speed and the probability of pedestrian fatality during a vehicle-pedestrian crash: A systematic review and meta-analysis. *Accident Analysis and Prevention*, 129, 241–249.
- [35] Ivan, J.N., Garrick, N.W., & Hanson, G. (2009). *Designing Roads that Guide Drivers to Choose Safer Speeds*. Report JHR 09-321. Storrs: University of Connecticut.
- [36] Jurewicz, C., Steinmetz, L., Phillips, C., Cairney, P., Veith, G., & McLean, J. (2014). *Improving Roadside Safety: Summary Report*. Publication AP-R437-14. Sydney: Austroads.
- [37] Jurewicz, C., Sobhani, A., Woolley, J., Dutschke, J., & Corben, B. (2016). Exploration of vehicle impact speed – injury severity relationships for application in safer road design. *Transportation Research Procedia*, 14, 4247–4256.
- [38] Kafoňková, J., & Andres, J. (2008). Nové poznatky v oblasti utváření bezpečných pozemních komunikací – silniční kategorie S 9,5 a S 11,5. *Silniční obzor*, 69, 290–292.
- [39] Kröyer, H.R.G. (2015). The relation between speed environment, age and injury outcome for bicyclists struck by a motorized vehicle – a comparison with pedestrians. *Accident Analysis and Prevention*, 76, 57–63.
- [40] Labi, S., Chen, S., Preckel, P.V., Qiao, Y., & Woldemariam, W. (2017). Rural two-lane highway shoulder and lane width policy evaluation using multiobjective optimization. *Transportmetrica A*, 13, 631–656.
- [41] Lamm, R., Psarianos, B., & Mailänder, T. (1999). *Highway Design and Traffic Safety Engineering Handbook*. New York: McGraw-Hill.
- [42] Lord, D., & Mannering, F. (2010). The statistical analysis of crash-frequency data: A review and assessment of methodological alternatives. *Transportation Research Part A*, 44, 291–305.
- [43] Martens, M., Comte, S., & Kaptein, N. (1997). *The Effects of Road Design on Speed Behaviour: A Literature Review*. MASTER project deliverable 2.
- [44] Martensen, H., & Dupont, E. (2013). Comparing single vehicle and multivehicle fatal road crashes: a joint analysis of road conditions, time variables and driver characteristics. *Accident Analysis and Prevention*, 60, 466–471.
- [45] OECD (1999). *Safety Strategies for Rural Roads*. Paris: Organisation for Economic Co-operation and Development (OECD).
- [46] OECD (2006). *Speed Management*. Paris: OECD.
- [47] OECD (2018). *Speed and Crash Risk*. Paris: OECD.
- [48] Ogden, K.W. (1997). *Safer Roads: A Guide to Road Safety Engineering*. Aldershot: Ashgate.
- [49] Papadimitriou, E., Filtness, A., Theofilatos, A., Ziakopoulos, A., Quigley, C., & Yannis, G. (2019). Review and ranking of crash risk factors related to the road infrastructure. *Accident Analysis and Prevention*, 125, 85–97.

- [50] Pokorný, P., Jensen, J. K., Gross, F., & Pitera, K. (2020). Safety effects of traffic lane and shoulder widths on two-lane undivided rural roads: A matched case-control study from Norway. *Accident Analysis and Prevention, 144*, No. 105614.
- [51] Radimský, M., Matuszková, R., Smělý, M., Kosňovský, M., Čepil, J., & Hornoch, O. (2014). *Metodika pro navrhování pozemních komunikací v uspořádání 2+1*. Brno: Brno University of Technology.
- [52] Reed, S., & Morris, A. (2012). Characteristics of fatal single-vehicle crashes in Europe. *International Journal of Crashworthiness, 17*, 655–664.
- [53] Reurings, M., Janssen, T., Eenink, R., Elvik, R., Cardoso, J., & Stefan, C. (2005). *Accident prediction models and road safety impact assessment: a state-of-the-art*. RIPCORD-ISEREST project deliverable D2.1.
- [54] Ruyters, H.G.J.C.M., Slop, M., & Wegman, F.C.M. (Eds.) (1994). *Safety effects of road design standards*. Report R-94-7. Leidschendam: SWOV Institute for Road Safety Research.
- [55] Shinar, D. (2017). *Traffic Safety and Human Behavior. Second Edition*. Bingley: Emerald.
- [56] Stamatiadis, N., Pigman, J., Sacksteder, J., Ruff, W., & Lord, D. (2009). *Impact of Shoulder Width and Median Width on Safety*. NCHRP Report 633. Washington: Transportation Research Board.
- [57] TRB (2003). *Application of European 2+1 Roadway Design*. NCHRP Research Results Digest 275. Washington: TRB.
- [58] TRB (2011). *Modeling Operating Speed: Synthesis Report*. Transportation Research Circular E-C151. Washington: TRB.
- [59] ÚNMZ (2018). *ČSN 73 6101 Projektování silnic a dálnic*. Prague: Czech Office for Standards, Metrology and Testing (ÚNMZ).
- [60] Usami, D.S. (2017). *Increase shoulder width*. Retrieved from www.RoadSafety-DSS.eu on March 25, 2020.
- [61] Wang, C., Quddus, M.A., & Ison, S.G. (2013). The effect of traffic and road characteristics on road safety: A review and future research direction. *Safety Science, 57*, 264–275.
- [62] Yannis, G., Dragomanovits, A., Laiou, A., La Torre, F., Domenichini, L., Richter, T., Ruhl, S., Graham, D., & Karathodorou, N. (2017). Road traffic accident prediction modelling: a literature review. *Proceedings of the Institution of Civil Engineers – Transport, 170*, 245–254.
- [63] Zegeer, C.V., & Perkins, D.D. (1980). Effect of Shoulder Width and Condition on Safety: A Critique of Current State of the Art. *Transportation Research Record, 757*, 25–34.
- [64] Zůvala, R., Bucsuházy, K., Valentová, V., & Frič, J. (2021). Representativeness of Czech In-Depth Accident Data. *Safety, 7*, 40.