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How does road marking in horizontal curves influence driving behaviour?

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Abstract

Purpose: Given the inconsistent application of various road markings on Czech rural roads, there is a question "How does road marking in horizontal curves influence driving behaviour?" The study objective was to assess how centreline and edgelines influence driving behaviour.

Methods: To focus on the critical conditions, six curves on secondary rural roads, with radii below 200 m, were selected and monitored before and after application of road marking. The studied indicators were average speed and lateral position, which were collected using trajectories detected in calibrated video recordings.

Results: The results indicated that speeds decreased in both edgeline and centreline applications; regarding lateral positions, the edgelines were associated with shifting the driving trajectories towards the centre of the road, and the centrelines were associated with shifting the driving trajectories towards the road edges.

Conclusions: The indicated trends are likely to be influenced also by other factors, such as specific curve radii values, superelevation, speed profile, or parameters of road surroundings. Following study should thus focus on collecting data in a larger sample of sites and building a cross-sectional model, statistically linking the mentioned characteristics with safety.

Keywords: Horizontal curve, Road marking, Edgeline, Centreline, Speed, Lateral position

1 Introduction

Horizontal road alignment is one of the general design features, which has a significant impact on driving and safety. Horizontal alignment consists of tangents (straight sections) connected by horizontal curves (further referred to as "curves") and other transition elements. Curve driving is influenced by perceptual factors, which refer to the driver's use of visual information to assess the curvature of an upcoming curve. Especially so called apparent radius is important, as it is the primary determining factor of speed at curve entry [1]. Further studies indicated the influence of other factors, such as curve visibility [2], presence of a lead vehicle [3], driver experience [4] or steering competence [5].

Curves are places of special interest for their higher accident risk compared to straight alignment due to additional centripetal forces exerted on a vehicle and higher driver cognitive workload [6]. Internationally, 25 to 30% of all fatal accidents occur on curves [7]. This amount is even higher in the Czech Republic, where more than one third of total road fatalities occur on curves; particularly critical are curves in rural sections of secondary roads [8]. Numerous analyses indicated that the curve accident risk increases with decreasing curve radii (i.e., increasing curve sharpness) [9]. This was also documented in a recent Czech study [10], which developed crash modification function for rural secondary roads and showed that the curves with the lowest radii (50 m) are approximately 3.7 times more hazardous than curves with radii 1000 m.

Another feature is road marking. Although it may be seen as a simplistic measure, it was found to be the most effective (i.e., with one of the highest cost-benefit ratios) low cost road safety treatment [11]. It consists mainly of longitudinal lines [12]:

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– Centreline separates opposite traffic streams: solid or dashed line, where it is (or it is not) allowed to cross, respectively.
– Edgelines mark the outer edge of the carriageway.
– Lane marking line separates traffic lanes for traffic in the same direction.

The aim of these lines is to ensure safe and comfortable driving by providing drivers with "reference points in the proximity of the vehicle and further ahead in the direction they are driving" [12].

In the context of two-lane rural roads, centreline and edgelines are used in most countries. Decision on their applications is usually based on road width. For example, Czech technical guidelines [13] recommend applying edgelines only on roads narrower than 6 m, and adding centrelines on wider roads; however, the guidelines are not mandatory. In other countries, centreline only is used on narrow roads, and edgelines are added on wider roads, however with several exceptions:

– For example, in Hungary, edgelines need not be added on less important roads [14].
– In Austria, adding centreline is allowed, but not obligatory [15].
– In Poland, application of edgelines may be limited only to hazardous locations [16].

In a sum, application of both centreline and edgelines is often inconsistent due to various local reasons and conditions. This is also the case on Czech rural roads, where no mandatory guidelines apply, and thus various configurations exist even on similar roads in one region (see example photographs in Fig. 1).

In theory, it would be valuable if applications would also consider impacts of road marking elements on driving behaviour (and safety). For example, Steyvers and De Waard [17] studied effects of two types of edgelines on Dutch rural roads, compared to two control sections, using video recordings and instrumented vehicle. Another Dutch study [18] presented a meta-analysis of studies that have evaluated the effects of edgelines on speed and lateral position of motorised road users. In total 41 and 65 estimates of the effects of an edgeline on speed and on lateral position, respectively, were extracted from the studies. Later, Burdett [19] analysed speed and speed variations on eight pairs of sites in New Zealand, comparing sites with edgelines and centreline to centreline-only sites, and a further set of centreline-only sites to sites with no markings.

The referred studies showed that it is suitable to analyse driving behaviour in terms of speed and lateral position. Interestingly, none of the studies focused specifically on curves. On the other hand, a different stream of research (e.g., [20–22]) focused on analysis of naturalistic driving (including speed and lateral position) in curves, however without specific consideration of road marking types. In addition, all the studies used cross-sectional approach, i.e. comparing similar sites with and without specific road marking. However, such comparison may be biased, since in reality the matched pairs may differ in other parameters – this is why before-after approach, i.e. evaluating the same sites in two time periods, has been recommended as more suitable observational study design [23].

To fill the indicated gap, the study objective was to assess how road marking, specifically centreline and edgelines, influences driving behaviour. To focus on the

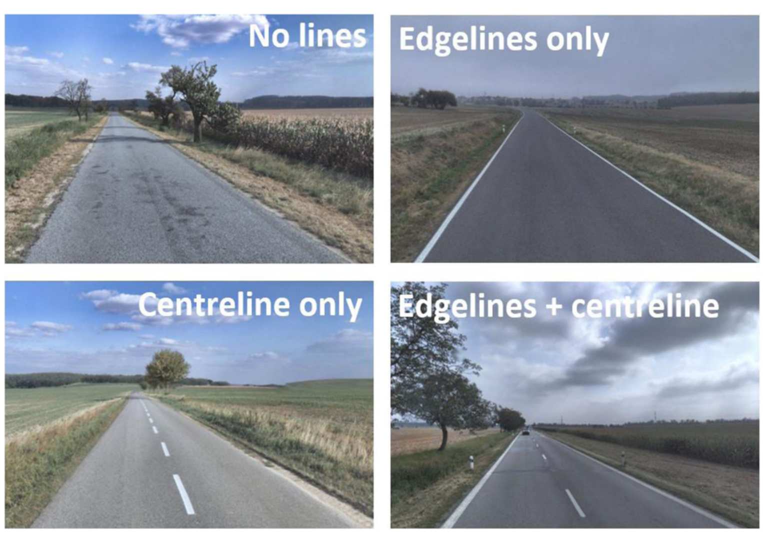


Fig. 1 Example photographs of Czech rural road marking scenarios (adapted from Mapy.cz)

critical conditions on Czech roads, we selected curves on secondary rural roads, with radii below 200 m. In addition, we distinguished between curve direction from driver perspective (driving in inside or outside lane), since some of previous studies indicated its influence on driving behaviour (e.g., [24–26]). Figure 2 illustrates the used terminology regarding curve direction.

Evaluation was conducted in a before-after design, i.e. comparing "no marking" to "marking" periods of identical road sites. Data and methods are described next, followed by results, and discussion and conclusions.

2 Data and methods

2.1 Field data collection

First, we discussed the study idea with responsible road authority in South Moravian region (SÚS JMK). With their help we identified six sites, which fulfilled following conditions:

- two-lane rural roads with pavement width 5–6 m
- horizontal curves with radii 100–200 m and relatively comparable lengths
- at that time without road marking, but planned to be marked by either centreline only or edgelines only
- with adjacent electricity poles to enable installation of video cameras

Figure 3 shows location of South Moravian region, as well as location of the six identified sites. Figure 4 provides photographs of the sites and Table 1 lists their main geometrical parameters (radii, widths, length of curves and tangents). In all curves default rural speed limit 90 km/h applied.

Sites 1–3 were planned to be marked by edgelines only, and sites 4–6 were planned to be marked by centreline only. The marking applied not only to the curves, but to the whole road section between intersections.

Next, after placing markers on the ground (using spray paint) for later calibration, we recorded video on each site for at least 96 h (4 days), both before and after marking. Recording took place in summer ("before" period) and autumn months ("after" period) of 2017, with approximately 1-month adaptation time between the periods. Recordings were taken in dry weather and good visibility conditions.

2.2 Camera calibration

To enable measurements in the recorded video records, we used the afore-mentioned markers to calibrate the cameras. From distances between the markers we calculated scale parameter, and their real-world coordinates. Then we calculated homography between these points in coordinate systems of image and real-world. This calibration enabled to map each image point onto a road plane and conduct measurements and calculations in real-world units (metres). For more details on the process, see Špaňhel et al. [27].

2.3 Detection and tracking of vehicles

First, we split video recordings into 1-h sessions, and discarded night-time footage, which could not be used for automated processing. Since traffic volumes were relatively low (approx. 400–600 veh/day, based on 2016 national traffic census), we detected all vehicles (both personal cars and vans). Vehicles were usually driving isolated, without oncoming traffic at the same time.

To detect vehicle licence plates in each video record image, we used ACF detector [28] for fast license plate detection. In the images with detected license plate, we detected the complete vehicles as well using Faster R-CNN neural network [29], which is considerably slower

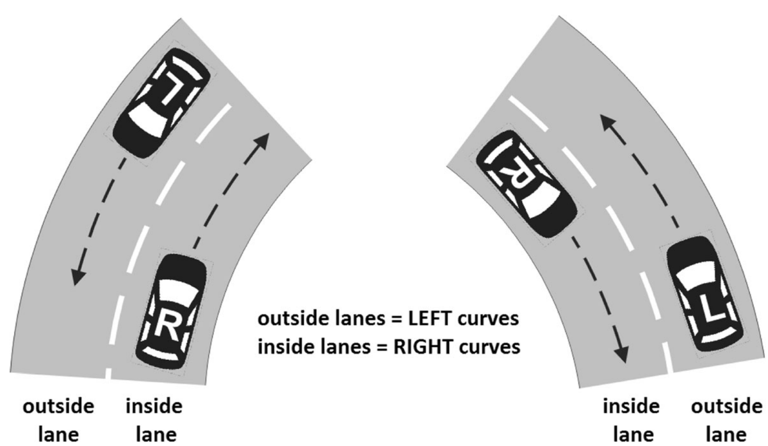


Fig. 2 Illustration of terminology: from driver perspective, outside/inside lanes are left/right curves (L/R)

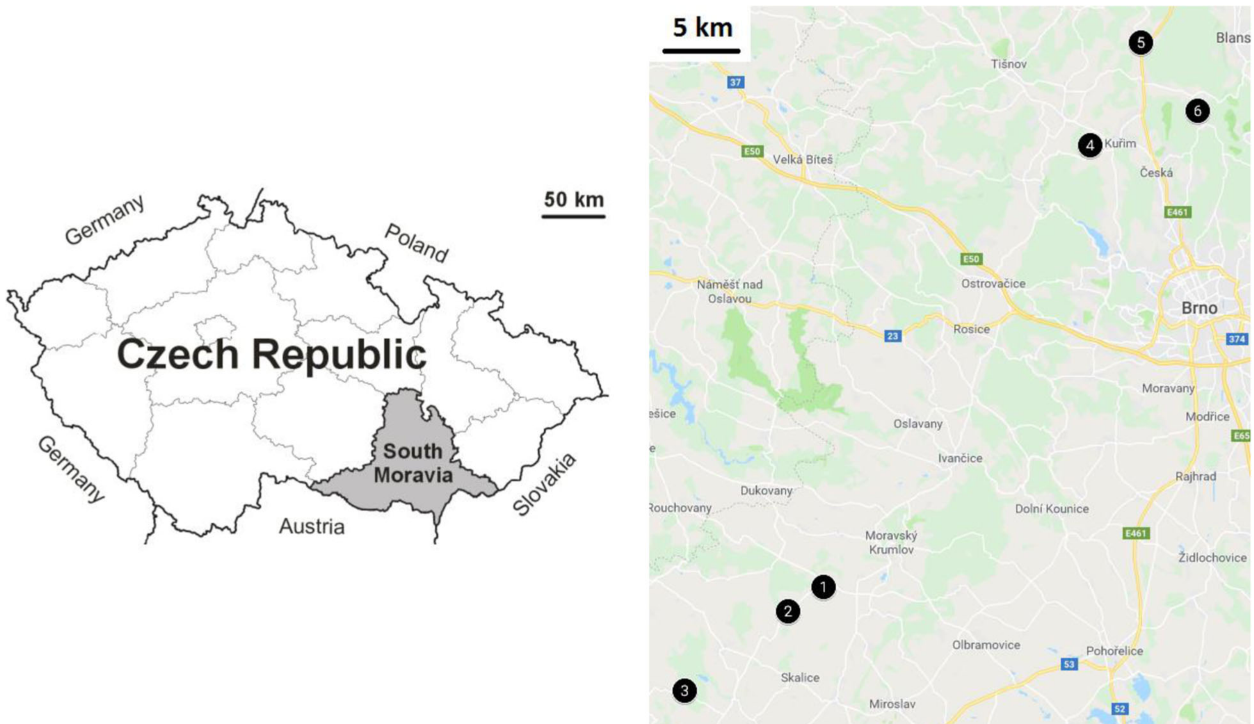


Fig. 3 Location of South Moravian region and the studied sites

Fig. 4 Photographs of the studied sites (adapted from Mapy.cz)

Table 1 Geometrical parameters of the studied sites

Geometrical parameters [m]	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6
Length of curve	56	53	62	46	57	59
Length of preceding tangent	400	240	450	105	95	110
Horizontal radius	110	100	102	110	120	135
Road width	5	6	5	6	6	6

but more suitable and precise for vehicle detection. Vehicles were tracked using Kalman filter. The position of a vehicle on the road plane was calculated as a projection of the license plate centre to the bottom edge of the detected vehicle, and transformation of this projected point using homography into the road plane (see Fig. 5), as described in the previous section. By this, we acquired a representative point in the ground plane. We defined three profiles in each curve. Next, we approximated the transformed positions by a cubic polynomial into trajectories. For each trajectory, we calculated intersections with three afore-mentioned profiles (see Fig. 5). Using driven distance and time differences, we obtained average speed between the first and third profile. Finally, we used the speed and trajectory data to obtain average speeds and series of lateral positions of each detected drive. Lateral positions were measured from the leftmost road edge.

To make sure that the obtained speed data are representative, we additionally conducted a test. On one site, we installed a roadside radar and measured a sample of 63 passing vehicle speeds. Then we paired this data with speeds from video tracking. Considering radar data a "ground truth", we calculated differences of tracking data and obtained an average value 1.98 km/h. Descriptive characteristics are reported in Table 2.

Boxplots of both data samples are shown in Fig. 6. Firstly, Shapiro-Wilk test proved the normality of samples. Secondly, we calculated the differences between values and tested those differences by using one sample *t*-test. The differences were found not statistically different from test value 2 (which was used as an approximation of mean difference 1.98 km/h).

Speeds obtained from tracking data are thus on average by 2 km/h higher compared to ground truth (radar data), which indicates absolute accuracy of the video analysis. Nevertheless, the absolute accuracy does not influence following analysis, which is in principle comparative.

Before the statistical analysis, obviously erroneous speed values were discarded. Final sample sizes and their main descriptive characteristics are listed in Table 3.

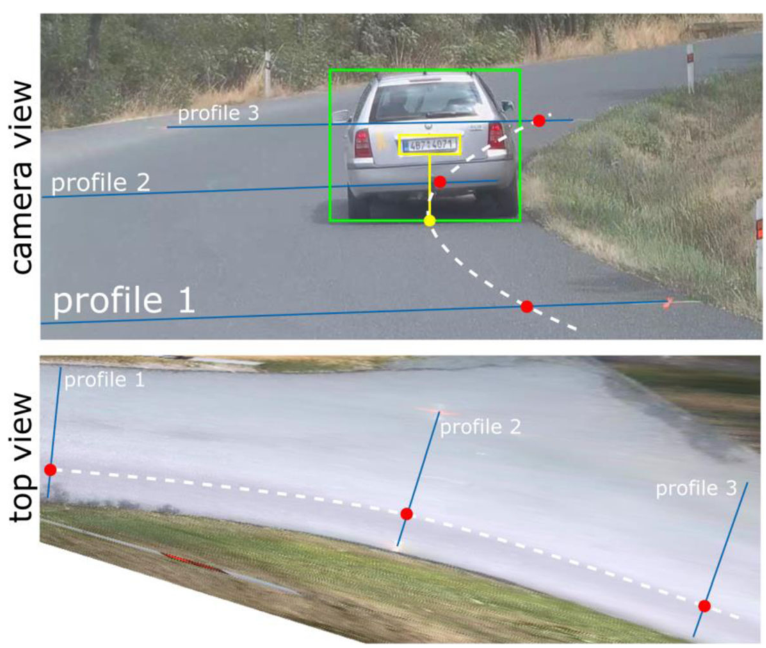


Fig. 5 Illustration of principle of video detection and tracking: in camera view, the position of vehicle on a road plane was calculated as a projection of a centre of vehicle license plate to the lowest detected edge; the transformed positions were approximated by a cubic polynomial into trajectories; and intersections with three profiles were calculated

Table 2 Descriptive characteristics of tracking and ground truth data samples and difference sample

	Sample of tracking data	Sample of ground truth data	Sample of differences
Min.	21.93	20.00	0.50
Max.	87.11	84.00	3.88
Mean	58.77	56.79	1.98
Median	57.69	56.00	1.94
Std. Dev.	13.56	13.29	0.68

Due to rejection of abnormal speed values, sample size of speed dataset is lower compared to dataset of lateral positions. Also note that it was not possible to distinguish speed values in individual profiles; therefore only lateral positions are reported in three profiles.

2.4 Statistical analysis

Our idea was to compare data samples "before marking" and "after marking", in terms of average speeds and lateral positions. Specifically, we used Shapiro-Wilk test to assess normality, followed by Mann-Whitney U test of equality of means in the two samples [30]. Both tests were performed at the 0.05 level of statistical significance.

Hypotheses were defined as follows:

$$H_0 : \left\{ \begin{matrix} \text{average speeds} \\ \text{lateral positions} \end{matrix} \right\} \text{in drives"before marking"and"after marking"ARE NOT different}$$

$$H_1 : \left\{ \begin{matrix} \text{average speeds} \\ \text{lateral positions} \end{matrix} \right\} \text{in drives"before marking"and"after marking"ARE different}$$

The statistical analysis was conducted in a statistical software IBM SPSS.

3 Results

According to Shapiro-Wilk test, none of the analysed samples was normally distributed. Mann-Whitney U test was used to assess equality of means in the sample pairs (before and after marking). Table 4 presents results of this test.

Bold values in Table 4 indicate average differences. These values enable following summary of results, related to original hypotheses, as listed in section 2.4:

- For curves after edgeline marking: In left curves (i.e., outside lanes), neither speeds nor lateral positions changed significantly. However, changes of both indicators were statistically significant in right

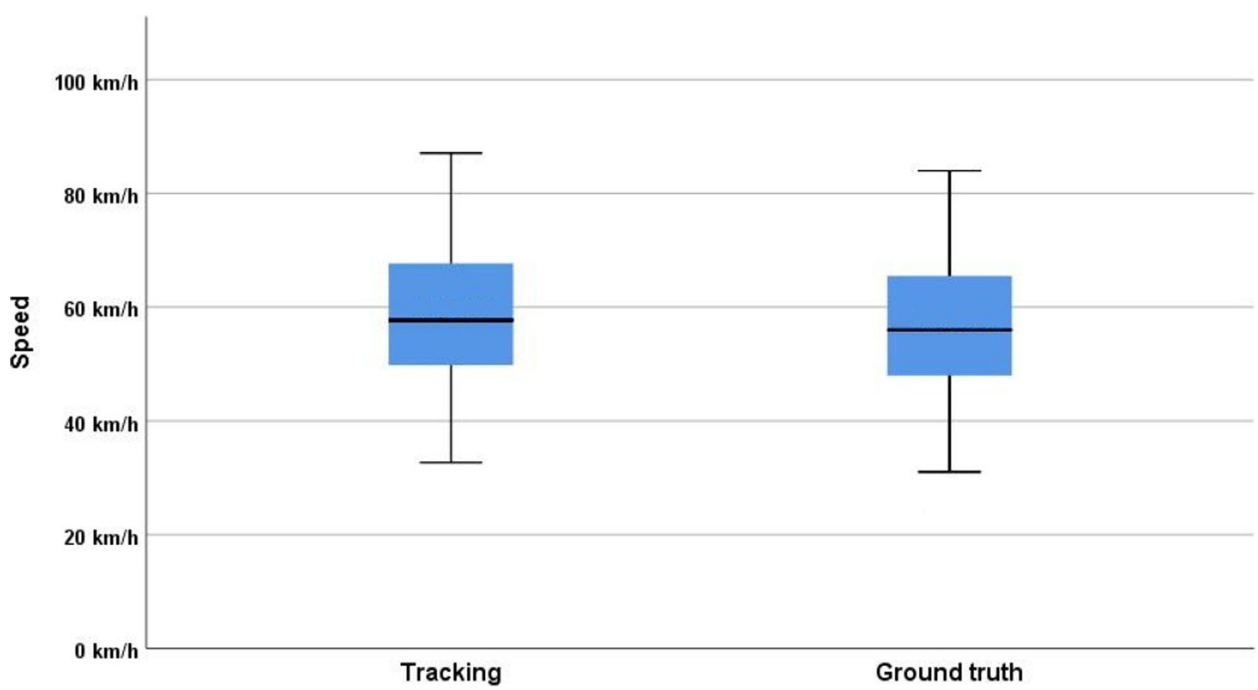


Fig. 6 Boxplots of samples of tracking and ground truth data

Table 3 Sample sizes (n) and descriptive characteristics of average speed and lateral position data

Indicator	Road marking	Curve direction	Measure-ment period	Profile number	*n*	Min.	Max.	Mean	Std. Dev.
Average speeds [km/h]	Edgelines	Left	Before	N/A	2024	38.30	99.00	65.92	9.91
			After		1651	36.60	100.80	65.68	11.06
		Right	Before		1164	39.10	92.80	68.31	9.61
			After		1075	38.00	96.70	64.16	9.63
	Centreline	Left	Before		2056	29.80	82.60	61.08	7.98
			After		1058	34.00	81.10	53.92	7.42
		Right	Before		1811	28.60	83.10	58.89	9.64
			After		1142	29.10	82.30	53.88	8.14
Lateral positions [m]	Edgelines	Left	Before	1	2246	0.24	4.76	2.21	0.66
				2	2477	0.08	4.77	2.70	0.80
				3	2156	0.25	4.77	2.53	0.82
			After	1	1893	0.26	4.44	2.15	0.58
				2	2116	0.29	4.51	2.65	0.74
				3	1652	0.25	4.50	2.57	0.69
		Right	Before	1	1954	1.51	5.89	3.76	0.65
				2	2204	1.72	6.38	4.53	0.83
				3	1486	1.73	5.88	4.71	0.67
			After	1	1556	1.91	5.25	3.53	0.45
				2	1708	1.97	5.49	4.31	0.57
				3	1281	2.11	5.78	4.30	0.55
	Centreline	Left	Before	1	2977	1.08	3.93	2.89	0.47
				2	2752	1.05	3.92	2.44	0.52
				3	2187	1.03	3.82	2.46	0.38
			After	1	1797	1.19	3.93	3.02	0.49
				2	1718	1.04	3.90	2.51	0.50
				3	1103	1.02	3.57	2.17	0.53
		Right	Before	1	2460	−0.09	2.69	1.03	0.50
				2	2343	−0.41	2.70	0.74	0.61
				3	1901	−0.60	2.69	0.72	0.48
			After	1	1609	0.14	2.68	0.87	0.32
				2	1620	−0.47	2.44	0.49	0.53
				3	1195	−1.24	2.63	0.22	0.74

curves (i.e., inside lanes): speeds decreased and trajectories moved towards outside edge of curve. It seems that, due to edgelines presence, drivers became more aware of road edges and thus chose less “sharp” trajectories closer to the centre of the road.

– For curves after centreline marking: In both left and right curves (outside and inside lanes), both speeds and lateral positions changed significantly: speeds were reduced and trajectories moved towards outside edge of curve. It seems that, due to centreline presence, drivers became more aware of driving in their own lane and thus shifted the trajectory further from the centreline (closer to the road edges).

Differences in trajectory positions are visualized in Fig. 7. Positions in three profiles enabled drawing approximate trajectories (in red before marking, in green after marking). To make the scheme clearer, individual lateral position differences are listed in the bottom table. Arrows at the bottom show the direction of trajectory positions measurement, starting from the leftmost road edge.

Table 4 Results of statistical testing of obtained differences

Indicator	Road marking type	Curve direction	Profile number	Difference	*p*-value	Significant difference?
Average speeds	Edgelines	Left	N/A	**−0.24**	0.168	**No**
		Right		**−4.15**	0.000	**Yes**
	Centreline	Left		**−7.16**	0.000	**Yes**
		Right		**−5.01**	0.000	**Yes**
Lateral positions	Edgelines	Left	1	−0.06	0.082	**No**
			2	−0.05	0.776	**No**
			3	+ 0.04	0.054	**No**
				Avg – 0.02		
		Right	1	−0.23	0.000	**Yes**
			2	−0.22	0.000	**Yes**
			3	−0.41	0.000	**Yes**
				Avg – 0.29		
	Centreline	Left	1	+ 0.13	0.000	**Yes**
			2	+ 0.07	0.000	**Yes**
			3	−0.29	0.000	**Yes**
				Avg – 0.03		
		Right	1	−0.16	0.000	**Yes**
			2	−0.25	0.000	**Yes**
			3	−0.50	0.000	**Yes**
				Avg – 0.30		

4 Discussion and conclusions

The study addressed the problem of inconsistent application of various road markings on Czech rural roads. It relates to the question: How does road marking in horizontal curves influence driving behaviour? The specific objective of the paper was to assess how centreline and edgelines influence driving behaviour. To focus on the critical conditions, we selected curves on secondary rural roads, with radii below 200 m. In total six sites were monitored in a before-after manner, i.e. comparing data in “no marking” and “marking” periods of identical sites. Indicators of average speed and lateral position were collected using trajectories detected in calibrated video recordings.

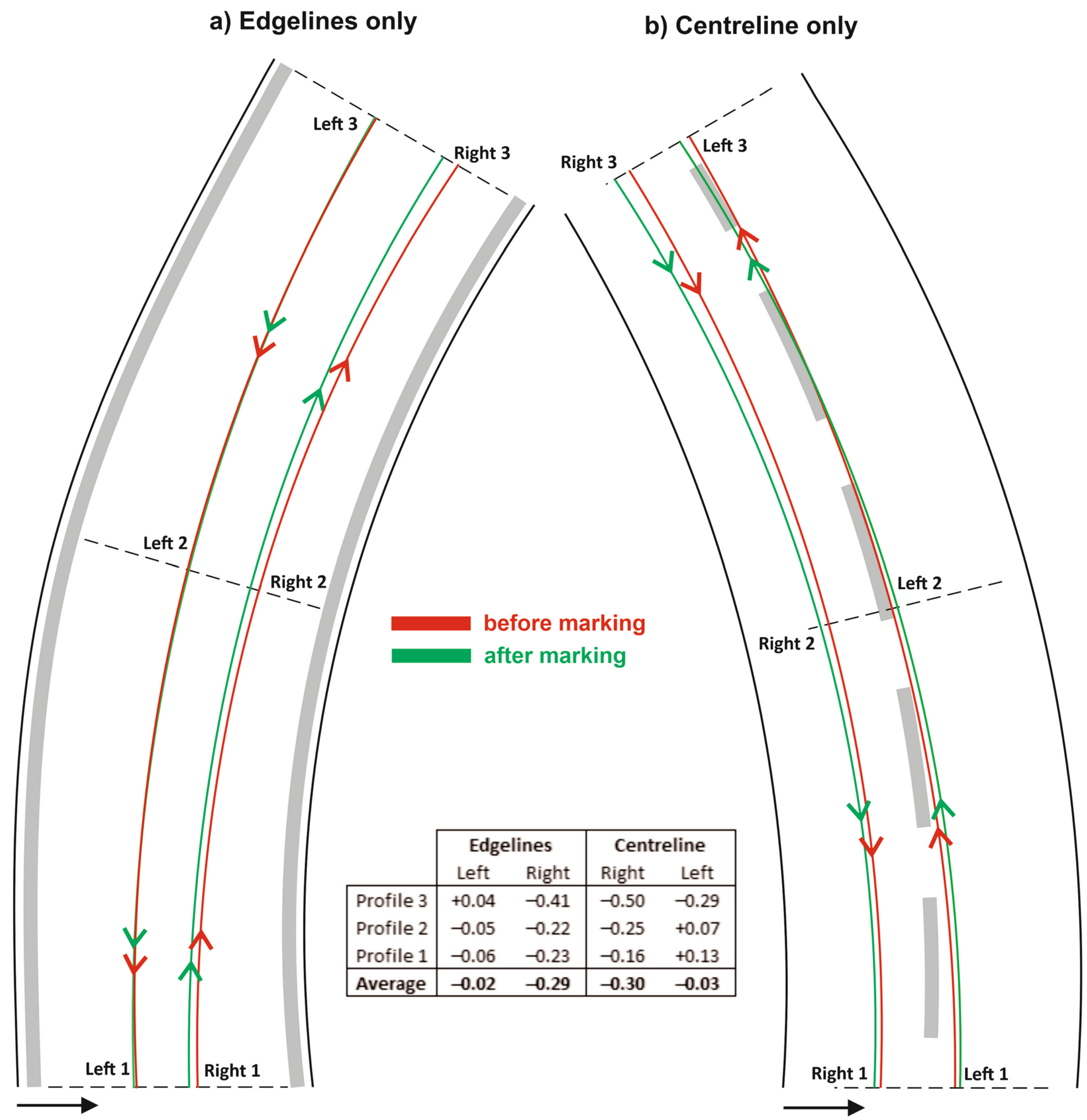
Based on the identified changes of indicators in before and after periods, following behaviours seemed to occur:

- In all curves (both after edgeline and centreline marking), average speeds decreased by approx. 4 to 7 km/h.
- In curves after edgeline marking, drivers became more aware of road edges and thus chose less sharp trajectories closer to the centre of the road (by approx. 0.3 m).
- In curves after centreline marking, drivers became more aware of driving in their own lane and thus shifted the trajectory further from the centreline, i.e., closer to the road edges (by up to 0.3 m).

Interestingly, some previous studies (e.g., [17, 19]) found the opposite trend – increased speeds after application of road markings. Nevertheless, the meta-analysis [18] concluded that the results of the evaluation studies showed a great variety in effects, including both negative and positive effects on speed and lateral position.

One of reasons may be that the past studies usually did not distinguish between curve directions, although they may differ in their effects on driving speed – both Hallmark et al. [24] and Othman et al. [26] found that right curves were associated with higher speeds. Specifically, in our study we identified two opposite tendencies in lateral positions: edgelines were associated with shifting the driving trajectories towards the centre of the road (in right curves only); the opposite trend held for the centrelines (in both left and right curves). It is not evident which effect may be more beneficial for safety, since both may result in increase of specific accident types (head-on vs run-off-the-road accidents). Further differences between previous studies and ours may be caused by the fact that the former often did not apply before-after comparison.

On the other hand, our study had some shortcomings:



	Edgelines		Centreline	
	Left	Right	Right	Left
Profile 3	+0.04	−0.41	−0.50	−0.29
Profile 2	−0.05	−0.22	−0.25	+0.07
Profile 1	−0.06	−0.23	−0.16	+0.13
Average	**−0.02**	**−0.29**	**−0.30**	**−0.03**

Fig. 7 Visual representation of approximate driving trajectories, based on obtained differences in lateral positions in three profiles (in table)

– *Sample size.* Only six sites were monitored. Unfortunately, this limitation is hardly avoidable, since road marking projects in the Czech Republic are infrequent and applied on a case-by-case basis only (not area-wide). Several previous studies probably also faced similar issues and thus dealt with limited samples: for example, Williston [31] studied 4 locations before and after edgelines application; Basile [32] mentioned earlier studies which monitored 8 and 12 study sections.

– *Road user characteristics*. In analysis, we did not consider potential differences between road users (drivers) and vehicle categories. Nevertheless, given the character of the studied locations, it is likely that traffic is mainly local, i.e., mostly residents are repeatedly driving there. In addition, we suppose that this character of road users and vehicle fleet traffic have not changed between before and after periods, and thus it does not invalidate the comparison.

– *Curve characteristics*. It is possible there were differences between the two curve groups (the ones selected for edgelines vs the ones selected for centrelines), as indicated for example by different magnitudes of standard deviations in Table 3, both before and after marking. There could be for example differences in visibility or road surroundings, such as presence of trees.

Neither video detection and tracking was perfect. The procedure did not allow distinguishing speeds in individual profiles; and since determination of speed and lateral position data was stepwise, it was not possible to pair both samples. Thus we could not discard lateral positions from drives, which were rejected due to erroneous speeds. These issues will be addressed in further stages of algorithm development.

To sum up, in our study we found two opposite tendencies in lateral positions during curve driving: the edgelines were associated with shifting the driving trajectories towards the centre of the road, and the centreline were associated with shifting the driving trajectories towards the road edges. However, these trends are likely to be influenced also by other factors, such as specific curve radii values, transition parameters, length of preceding tangent, superelevation, or speed profile characteristics, e.g., speed before the curve.

Following study should focus on the mentioned limitations by collecting data in a larger sample of sites, ideally including data on road users as well as environment (daytime/night-time, weather, season, etc.), and building a cross-sectional statistical model (so called accident prediction model), using the mentioned characteristics as potential explanatory variables. In case of adding also non-intervention sites (without any road marking) as a comparison group, effectiveness study could also be carried out.

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Authors' contributions
PH, JA and VV developed the methodology. PH planned and oversaw the field data collection. JŠ and AH calibrated the videos and conducted vehicle detection and tracking. PH and RZ performed the statistical analysis and interpreted the results. JA drafted the manuscript and finalized it with help of PH, RZ and VV. The authors read and approved the final manuscript.

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Availability of data and materials
The datasets analysed during the current study are available from the corresponding author on reasonable request.

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
Not applicable.

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