

THE INFLUENCE OF ROAD MARKING VISIBILITY ON LATERAL VEHICLE POSITION AND DRIVING SPEED

IVANA KUČINA^{a,*}, BERNARD KOSOVEC^a, FILIP JEZIDŽIĆ^b, MARIJA FERKO^{a,b},
DARKO BABIĆ^a

^a University of Zagreb, Faculty of Transport and Traffic Sciences, Department of Traffic Signaling, Vukelićeva 4, 10 000 Zagreb, Republic of Croatia

^b Smart View d.o.o., Rastočka 8a/2, 10020 Zagreb, Republic of Croatia

* corresponding author: ivana.kucina@fpz.unizg.hr

ABSTRACT. Road markings are a vital element of horizontal signalling, forming an integral part of traffic signalling. Their role in traffic safety involves providing timely warnings, safe guidance, and necessary information to ensure the safe movement of all road users. Under conditions of reduced visibility, often due to weather (night, fog, rain, etc.), road markings are often the only guide for drivers to determine the direction of the road. Research conducted using a driving simulator demonstrated the influence of road markings on driver behaviour, specifically on lateral vehicle position and driving speed. The results indicated that drivers behave differently depending on the visibility of road markings. A total of 31 participants took part in the study, with data collected on driving speed and lateral vehicle position for three different visibility levels of road markings on a straight road and on a right and left curve.

KEYWORDS: Road markings, visibility, driving simulator, driving speed, lateral position.

1. INTRODUCTION

Road markings are a crucial traffic management component, providing visual guidance for drivers and other road users. Together with traffic signs, they are one of the most cost-effective measures for improving road safety [1].

The visibility of road markings depends on several factors, including the type of road marking material, the position of the marking, the number of markings, their age, the type of road, average annual daily traffic (AADT), speed limits, the amount of salt and abrasive used and winter maintenance activities [2]. Additionally, the quality and quantity of glass beads play a crucial role, as they directly affect the visibility and retroreflection of the markings [3–6].

The visibility of road markings is crucial for drivers and Advanced Driver Assistance Systems (ADAS) and the development of autonomous vehicles. Research from 2017 showed that camera-based detection of road markings improves with increased visibility, specifically with higher retroreflection and contrast ratios [7]. The colour of the road markings also affects their visibility and detection. For example, yellow markings on concrete pavements are more difficult for ADAS systems to detect due to lower contrast than white markings [8].

The evolution of road markings has prompted numerous studies on selecting materials and maintenance methods and assessing the impact of these markings on driver behaviour under varying conditions. Many studies have examined the influence of longitudinal road marking widths and various treatments (transverse

lines, chevron markings, dragon teeth, herringbone patterns, optical circles, horizontal warning signs, etc.) on driving speed and the lateral position of vehicles. Most of these studies assessed the effect of longitudinal marking widths on speed reduction [9, 10] and the impact of different treatments on the reduction of driving speed [11–17].

Some research has also focused on the effect of longitudinal marking widths on a vehicle's lateral position, contributing to enhanced road safety. Wider longitudinal markings have been shown to reduce traffic accidents [18, 19]. Optical circles [16] and red median markings [17] significantly affect lateral positioning, while herringbone patterns were found not to influence lateral position in Ariën et al. [15] study. However, Charlton [20], Awan et al. [16], and Kazemzadehazad et al. [21] reported a significant impact lateral position. However, plain double yellow centre lines showed no noticeable effect on lateral vehicle position [20].

Drivers obtain over 90% of traffic-related information through their sense of sight. Since pavement markings and traffic signs are vital sources of this information, their visibility is critical, especially during night-time and in low-visibility conditions. The research primarily focuses on determining the minimum visibility levels of road markings and analysing how their visibility affects driver behaviour. Previous research indicates that the minimum retroreflection needed by drivers for safe night driving in dry conditions ranges between 100 and 150 mcd lx⁻¹ m⁻² [22–25].

Limited research has explored the impact of visibility levels at night on bus traffic safety. The visibility

of pavement markings does not significantly affect the frequency of night-time crashes [26, 27]. Some studies have shown that improving visibility or having lower levels of retroreflection can reduce the frequency of collisions in both dry [28–30] and wet conditions [31, 32]. In conditions of reduced visibility, driving speed tends to decrease, whereas in conditions of higher visibility, driving speed increases [33–35]. A recent study by Fiolić et al. [35] found no significant differences in the vehicle’s lateral position at varying levels of visibility.

The paper aims to determine whether the different visibility of road markings affects the driver’s behaviour, specifically regarding speed and lateral vehicle position. The research is based on data collected from a driving simulator.

2. RESEARCH METHODOLOGY

The research was carried out using a static driving simulator from Carnetsoft B.V. The simulator setup includes a driver section consisting of a seat with pedals, a steering wheel, and a gear shifter, along with three interconnected 30-inch displays. These displays offer a combined resolution of 5760×1080 and operate at a frame rate of 30 Hz. The screens provide a 210° panoramic view of the environment through six channels: left, middle, and right views, along with three mirror displays. The middle screen also presents the vehicle’s control panel, which includes the speedometer, rev counter, turn signals, lighting, fuel gauge, and other indicators. This setup enhances the realism of the driving experience. The simulation software operates on a computer running Windows 10 (64-bit), with 8 GB of RAM and 4 GB of storage, ensuring smooth operation of the driving simulator (Figure 1).

Three driving scenarios were used in the research, each divided into two parts. The total length of the scenario is 12.5 km, with the first part covering 2.24 km and the second part 10.26 km. The average driving time in the simulator ranges from 10 to 15 minutes, depending on speed. The first part, a warm-up, lasted approximately 2-3 minutes, depending on driving speed. The second part, where the actual research takes place, consists of three stages featuring identical road elements: a straight section, a right turn, and a left turn. However, these stages differ in the visibility of the road markings, with three levels: poor visibility (V1), medium visibility (V2), and high visibility (V3) (Figure 2). The scenarios differ in the sequence of these stages, with varying levels of road marking visibility for each. All scenarios occur on a two-way road outside urban areas, with a total roadway width of 6.50 meters (3.25 meters per driving lane). The simulation replicates night driving conditions, and all participants drove with low beams to ensure consistent conditions. The driving scenario don’t include vehicles from the opposite direction to avoid influencing the participant’s behavior.



FIGURE 1. Driving simulator setup.



FIGURE 2. Scenarios: a) V1 – poor visibility, b) V2 – medium visibility, c) V3 – high visibility.

The participant begins driving in the first stage, where road marking visibility is at its lowest (V1). This stage starts on a 150-meter straight section, with a posted speed limit of 90 km h^{-1} (sign dimensions: 60 cm, height: 1.5 m, distance from edge: 1 m). Afterwards, the participant drives through a 500-meter flat section, where data on speed and vehicle lateral position is collected. This is followed by another 150-meter stretch with traffic signs indicating an upcoming right turn (sign dimensions: 90 cm, height: 2.3 m, distance from edge: 1 m) and a speed limit of 70 km h^{-1} (sign dimensions: 60 cm, height: 1.5 m, distance from edge: 1.5 m).

The right turn begins with a 50-meter transition with a 200-meter radius, leading into a 110-meter turn with a 150-meter radius, and concludes with another 50-meter section with a 200-meter radius. Sharp turn signs (dimensions: 60 cm, height: 1.5 m, distance from edge: 7.5 m) are placed 37, 73.5, and 110 meters before the turn begins. After that, there is a 150-meter straight section with signs indicating

an upcoming left turn and a speed limit, followed by a left turn identical to the right turn. The participant then approaches a four-way intersection where they have the right of way, transitioning to the second stage of the scenario. In this stage, road marking visibility is at a medium level (V2). The participant first navigates through the left turn, then a straight section, followed by the right turn, and finally, another intersection where they again have the right of way. In the third and final stage, where road marking visibility is at its highest (V3), the participant drives through a right turn, a left turn, and ends on a straight section, concluding the test. The exact sequence applies to the other two scenarios, with the order of the straight sections and the right and left turns being the only difference.

At the start of the study, participants were provided with detailed instructions, after which they signed a consent form. Additionally, they completed a questionnaire that collected personal information such as date of birth, gender, date of obtaining a driver's license, self-assessment of driving ability, driving frequency, estimated kilometres driven per year, and any vision problems.

Participants were also required to complete a self-assessment of their psychophysical condition before and after the driving simulation. It was explained that mild nausea might occur during the simulation, and the session should immediately stop if they experienced symptoms such as headache, discomfort, or nausea for safety reasons. Participants were instructed to drive using only the low-beam headlights. It was emphasized that the study was not assessing their driving quality, and no penalties would be imposed for traffic violations. After the driving session, participants completed another form to assess their general condition post-simulation, aiming to identify any changes in their psychophysical state.

The study involved 31 adult participants, all required to have a driver's license of at least category B. Of the 31 participants, 10 were women (32.26%) and 21 were men (67.74%). The average age of participants was 26.68 years (Min = 18.89 years, Max = 32.69 years, SD = 2.92 years), and the average driving experience was 7.03 years (Min = 0.77 years, Max = 14.66 years, SD = 3.07 years). Participants rated their driving skills on a scale from 1 to 5, with an average score of 4.06 (Min = 3, Max = 5, SD = 0.62). The estimated annual distance driven by participants averaged 12 354.84 kilometres (Min = 1 000 km, Max = 50 000 km, SD = 12 149.07 km).

3. RESULTS

The conducted analysis aimed to determine whether and to what extent different levels of road marking visibility, or the quality of road markings, affect driver behaviour. This study observed two key variables: vehicle speed and lateral position. A one-way ANOVA was conducted to analyse the impact of visibility on

these variables across three distinct sections of the road. A comparison was made between the impact of different levels of visibility of road markings on certain road sections on the driving speed and lateral position.

3.1. DESCRIPTIVES

The descriptive statistics for speed and lateral position across different visibility levels and road sections provide detailed insights into driver behaviour in the driving simulator study.

The descriptive statistics analysis for the left curve section shows that the mean speed for different levels of road marking visibility (poor, medium, high) remains relatively consistent, ranging from 25.574 m s^{-1} to 26.243 m s^{-1} . The standard deviation of speed is also stable across visibility conditions, indicating similar variability in driving speed under all three conditions. For the lateral position on the left curve, the means are close to zero for all visibility levels, suggesting that drivers, on average, maintained their position near the centre of the lane. However, the standard deviation of lateral position, which ranges from 0.379 m to 0.419 m, indicates a noticeable variation in how consistently drivers maintained their position. Poor road marking visibility has a slightly higher standard deviation (0.419 m) than medium (0.379 m) and high (0.393 m) visibility conditions, implying greater deviation from the centreline under poor visibility.

In the right curve section, speed remained stable, with mean values between 25.632 m s^{-1} and 25.694 m s^{-1} across different levels of road marking visibility. The standard deviation for speed was again similar, indicating no significant change in speed variability based on the visibility of road markings. However, the lateral position shows more variation in standard deviation, especially in poor visibility (0.429 m). This suggests that drivers had considerable variability in maintaining their lateral position under poor visibility conditions.

In the straight road section, speeds were slightly higher, with the mean ranging from 26.598 m s^{-1} to 27.037 m s^{-1} . The standard deviation for speed remains consistent across visibility levels. For lateral position, the standard deviation under poor visibility was 0.333 m, increasing to 0.382 m under high visibility. This indicates slightly more variability in lateral position under high visibility conditions, potentially due to drivers feeling more confident and adjusting their position more frequently.

The following multiple comparisons were crucial to understanding whether these observed mean differences were statistically significant across different levels of road marking visibility. Given that road marking visibility impacts both speed and lateral position, conducting post-hoc tests to identify specific pairs of visibility conditions that differed significantly was important. These comparisons help clarify road

Road section	Variable	Visibility	N	Mean	Std. Deviation	Std. Error	Minimum	Maximum
Left curve	Speed [m s^{-1}]	Poor	12,126	25.574	5.757	0.052	14.490	37.657
		Medium	11,858	26.168	5.841	0.054	12.764	37.653
		High	11,821	26.243	5.621	0.052	16.706	37.660
		Total	35,805	25.992	5.748	0.030	12.764	37.660
	Lateral position [m]	Poor	12,126	0.107	0.393	0.004	-1.238	1.434
		Medium	11,858	0.115	0.379	0.003	-1.433	1.232
		High	11,821	0.090	0.419	0.004	-0.906	1.485
		Total	35,805	0.104	0.397	0.002	-1.433	1.485
Right curve	Speed [m s^{-1}]	Poor	33,139	25.632	5.291	0.029	12.032	37.663
		Medium	33,061	25.694	5.124	0.028	16.070	37.663
		High	33,130	25.641	5.243	0.029	15.249	37.661
		Total	99,330	25.656	5.220	0.017	12.032	37.663
	Lateral position [m]	Poor	33,139	0.028	0.429	0.002	-2.193	2.834
		Medium	33,061	0.012	0.400	0.002	-1.201	1.983
		High	33,130	0.019	0.408	0.002	-2.426	2.084
		Total	99,330	0.019	0.412	0.001	-2.426	2.834
Straight road	Speed [m s^{-1}]	Poor	18,619	26.598	4.614	0.034	17.572	37.662
		Medium	18,312	27.037	4.706	0.035	18.543	37.626
		High	18,342	27.008	4.722	0.035	16.402	37.627
		Total	55,273	26.880	4.685	0.020	16.402	37.662
	Lateral position [m]	Poor	18,620	0.109	0.333	0.002	-1.157	2.091
		Medium	18,312	0.078	0.326	0.002	-0.884	1.082
		High	18,342	0.092	0.382	0.003	-1.163	1.324
		Total	55,274	0.093	0.348	0.001	-1.163	2.091

TABLE 1. Descriptive statistics.

marking quality's nuanced effects on driving behaviour across various road sections.

3.2. LEFT CURVE

Levene's Test of Homogeneity of Variances for both speed and lateral position showed that the assumption of equal variances is violated for the left curve section, as all the p -values are less than 0.001. Because of that, we used Welch's ANOVA and Brown-Forsythe tests to determine whether there was a significant difference between the observed groups.

Both the Welch and Brown-Forsythe tests were significant ($p < 0.001$), indicating a statistically significant difference in speed across the three levels of road marking visibility on the left curve. This section's road marking visibility levels (low, medium, high) affect vehicle speed significantly. Similarly, both tests showed a statistically significant difference in lateral position across the visibility levels ($p < 0.001$), meaning that road marking quality affects vehicle lateral position significantly on the left curve. Next, we proceeded with multiple comparisons using the Games-Howell post hoc test.

The Games-Howell post hoc test results revealed significant speed and lateral position differences across road marking visibility levels. For speed, both poor and medium visibility resulted in significantly lower speeds compared to high visibility of road markings (MD = -0.593 m s^{-1} and -0.669 m s^{-1} , respectively,

both $p < 0.001$). However, no significant difference was found between medium and high visibility ($p = 0.568$).

For lateral position, significant differences were observed between poor and high visibility of road markings (MD = 0.017 m, $p = 0.003$) and between medium and high visibility (MD = 0.025 m, $p < 0.001$). These results indicate that vehicles tend to deviate less from the centre in high visibility conditions compared to poor visibility. No significant differences were found between poor and medium visibility for lateral position ($p = 0.303$).

3.3. RIGHT CURVE

Levene's Test of Homogeneity of Variances for the right curve section revealed different speed and lateral position results. For speed, the test showed significant results ($p < 0.001$), indicating that the assumption of equal variances is violated across the visibility levels. In contrast, the p -values were greater than 0.05 for the lateral position, suggesting that the assumption of homogeneity of variances is met. Based on these results, we used Welch's ANOVA to compare speeds and standard ANOVA to compare lateral positions.

The Robust Tests of Equality of Means for speed on the right curve yielded the following results: Welch Statistic = 1.371, with $p = 0.254$ and Brown-Forsythe Statistic = 1.349, with $p = 0.260$. Both tests indicated no statistically significant difference in speed across

Dependent Variable	Visibility (I)	Visibility (J)	Mean Difference (I-J)	Std. Error	Sig.
Speed [m s ⁻¹]	Poor	Medium	-0.593*	0.075	< 0.000
		High	-0.669*	0.074	< 0.000
	Medium	High	-0.076	0.074	0.568
Lateral position [m]	Poor	Medium	-0.007	0.005	0.303
		High	0.017*	0.005	0.003
	Medium	High	0.025*	0.005	< 0.000

* The mean difference is significant at the 0.05 level.

TABLE 2. Multiple comparisons (Games-Howell post hoc tests) for the left curve.

Dependent Variable	Visibility (I)	Visibility (J)	Mean Difference (I-J)	Std. Error	Sig.
Lateral position [m]	Poor	Medium	0.016*	0.003	< 0.000
		High	0.009*	0.003	0.013
	Medium	High	-0.007	0.003	0.066

* The mean difference is significant at the 0.05 level.

TABLE 3. Multiple comparisons (Tukey HSD post hoc tests) for the right curve.

the three visibility levels (poor, medium, and high) since the p -values are greater than 0.05. The results suggest that variations in road marking visibility do not significantly influence vehicle speed on the right curve. Since the result was not significant, there is no need for post hoc comparisons for speed on the right curve.

The results of the ANOVA for lateral position on the right curve revealed a statistically significant difference across the three visibility levels, with an F -statistic of 12.895 and a p -value of less than 0.001. This indicates that road marking quality impacts how vehicles position themselves laterally on this road section. Given the significance of these findings, further post-hoc analysis was conducted to identify which specific visibility levels (poor, medium, high) differ from each other in terms of lateral positioning.

The Tukey HSD post hoc analysis for lateral position revealed significant differences between the levels of road marking visibility. Specifically, vehicles in the poor road marking visibility condition exhibited a significantly greater lateral position compared to those in the medium ($MD = 0.016$ m, $p < 0.001$) and the high road marking visibility condition ($MD = 0.009$ m, $p = 0.013$). Conversely, there was no significant difference in lateral position between medium and high road marking visibility ($MD = -0.007$ m, $p = 0.066$).

3.4. STRAIGHT ROAD

Levene's Test of Homogeneity of Variances results for the straight road section indicated significant violations of the assumption for both speed and lateral position, with p -values less than 0.001, suggesting that the variances are unequal across the visibility levels for both variables. Consequently, Welch's ANOVA

was utilized to compare means and determine the differences in speed and lateral position across the three road marking visibility conditions.

The Robust Tests of Equality of Means results for the straight road section revealed significant differences in speed and lateral position across the three levels of road marking visibility. Specifically, the Welch statistic for speed was 51.611 ($p < 0.001$), and for lateral position, it was 42.709 ($p < 0.001$). These findings indicate that variations in road marking visibility significantly influence vehicle speed and lateral positioning. Consequently, post hoc analyses are necessary to determine the differences between the visibility levels.

The Games-Howell post-hoc analysis for the straight road section revealed significant differences in both speed and lateral position across the visibility levels. For speed, vehicles in the poor road marking visibility condition drove significantly slower than those in the medium ($MD = -0.438$ km h⁻¹, $p < 0.001$) and high road marking visibility conditions ($MD = -0.410$ km h⁻¹, $p < 0.001$). There was no significant difference in speed between medium and high visibility ($p = 0.832$). In terms of lateral position, vehicles in the poor road marking visibility condition showed a significantly greater lateral position movement compared to both medium ($MD = 0.032$ m, $p < 0.001$) and high road marking visibility conditions ($MD = 0.018$ m, $p < 0.001$). Additionally, vehicles in the medium road marking visibility condition also had a significantly greater lateral position movement than those in the high visibility condition ($MD = -0.014$ m, $p < 0.001$).

Dependent Variable	Visibility (I)	Visibility (J)	Mean Difference (I-J)	Std. Error	Sig.
Speed [m s ⁻¹]	Poor	Medium	-0.438*	0.049	< 0.000
		High	-0.410*	0.049	< 0.000
	Medium	High	0.028	0.049	0.832
Lateral position [m]	Poor	Medium	0.032*	0.003	< 0.000
		High	0.018*	0.004	< 0.000
	Medium	High	-0.014*	0.004	< 0.000

* The mean difference is significant at the 0.05 level.

TABLE 4. Multiple comparisons (Games-Howell post hoc tests) for the left curve.

4. DISCUSSION

This study investigated how different levels of road marking visibility impact driver behaviour, mainly focusing on speed and lateral position, across three distinct road sections: left curve, right curve, and straight road. The findings reveal several notable trends in how road marking visibility influences driving performance, contributing to the broader understanding of road safety and driver behaviour in varying visibility conditions.

4.1. SPEED AND ROAD MARKING VISIBILITY

Across all road sections, the analysis revealed that speed was generally higher in the straight road section compared to the left and right curves, regardless of visibility level. In particular, the straight road saw the highest average speed under medium visibility conditions (27.037 m s⁻¹). Interestingly, in the left curve section, while differences in speed between poor, medium, and high visibility were statistically significant, these differences were relatively small, ranging from 25.574 m s⁻¹ to 26.243 m s⁻¹. The Games-Howell post hoc test confirmed that speeds in the poor and medium visibility conditions were significantly lower than in the high visibility condition (MD = -0.593 m s⁻¹ and MD = -0.669 m s⁻¹, respectively), suggesting that improved road marking visibility encourages drivers to maintain slightly higher speeds on curves. A similar finding regarding reduced driving speeds in low-visibility conditions and increased speeds in better visibility was observed in previous studies [33–35].

The speed remained consistent across all visibility levels on the right curve, with no statistically significant differences. This finding suggests that the geometric challenge of the right-directed curve may substantially influence driving speed more than road marking visibility, leading drivers to adopt more cautious speeds irrespective of visibility.

For the straight road, visibility had a more pronounced impact on speed. Vehicles in the poor road marking visibility conditions drove significantly slower than those in both the medium (MD = -0.438 m s⁻¹) and high visibility conditions (MD = -0.410 m s⁻¹).

Higher driving speeds in response to better road marking visibility are attributed to the driver's increased sense of security. With greater detection distances, drivers can follow the road more clearly and prepare for upcoming situations. This is supported by research showing that increasing the retroreflectivity of road markings improves detection distance. For example, road markings with a retroreflection of 100 mcd lx⁻¹ m⁻² are visible from 91.44 meters away [23, 36]. However, there was no significant difference in speed between medium and high visibility, indicating that further improvements may not significantly alter driving speed once visibility reaches a medium threshold.

4.2. LATERAL POSITION AND ROAD MARKING VISIBILITY

Lateral position, which indicates how consistently drivers maintained their position within the lane, also showed significant variability based on road marking visibility. In the left curve section, road marking visibility had a significant effect, with vehicles in high visibility conditions deviating less from the centreline than those in poor and medium road marking visibility conditions (MD = 0.017 m and MD = 0.025 m, respectively). These results suggest that higher-quality road markings help drivers maintain a more consistent lane position on curves, potentially reducing the risk of lane departures.

Similarly, lateral position varied significantly on the right curve between visibility conditions. Vehicles in poor visibility had a more significant lateral deviation than those in medium and high visibility conditions (MD = 0.016 m and MD = 0.009 m, respectively), indicating that poor road markings may cause drivers to struggle to maintain the lane position, particularly in curved sections.

On the straight road, the pattern was similar, with significant differences in lateral position between poor, medium, and high visibility conditions. Drivers in poor road marking visibility conditions exhibited the greatest lateral deviation, while those in high visibility conditions maintained the most consistent lane position. The medium visibility condition also showed

more significant lateral deviation than the high visibility condition, supporting the statement that improved road markings lead to better lateral control, even on straight road sections.

Previous studies also confirm the fact that the visibility of road markings impacts a vehicle's lateral position. Specifically, reduced visibility of these markings results in a more erratic lateral position, both on straight sections and in curves [37, 38]. However, since different road marking treatments (transverse lines, dragon teeth, herringbone patterns, optical circles, etc.) do affect a vehicle's lateral position in curves [14–17]. Further research is needed to explore how the visibility of various road markings influences a vehicle's positioning within the traffic lane.

5. CONCLUSIONS

The visibility of road markings is a crucial factor in traffic safety, as over 90 % of information is obtained through vision. Research has shown that visibility impacts driver behavior. The results of the study can help experts and practitioners in understanding how markings affect drivers in night-time conditions and in making decisions related to the implementation of particular materials for markings, as well as for planning the maintenance activities. Therefore, it is necessary to properly maintain markings and signs in order to maintain an adequate level of visibility and thus ensure of increasing road safety. Road markings must be properly and consistently maintained to ensure adequate visibility.

One limitation of the study is that it was conducted using a driving simulator, which cannot fully replicate the complexity of real-world driving. Additionally, the number and age of participants may have influenced the results, presenting another limitation.

Future research should also consider various weather conditions, such as rain, fog, and snow, during night-time, and include a larger pool of participants. The findings from the driving simulator should be compared with data from studies conducted under real road conditions, where sections of the road would feature markings with varying levels of visibility (high, medium, and low).

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