IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received 11 January 2023, accepted 17 January 2023, date of publication 20 January 2023, date of current version 25 January 2023.

Digital Object Identifier 10.1109/ACCESS.2023.3238578

RESEARCH ARTICLE

Examining the Impact of Distance Between VSL Road Signs on Vehicle Speed Variance

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This work was supported by the Polish National Centre through the Research and Development Project (NCBR), European Regional Development Fund "INZNAK: Intelligent Road Signs with V2X Interface for Adaptive Traffic Controlling," under Grant POIR.04.01.04-00-0089/16.

ABSTRACT Variable speed limit (VSL) is an intelligent transportation system (ITS) solution for traffic management. The speed limits can be changed dynamically to adapt to traffic conditions such as visibility and traffic volume, curvature, and grip coefficient of the road surface. The VSL traffic sign location problem and attempts to solve it using computer simulation are presented in this paper. Experiments on a selected road segment, carried out using the traffic simulator, have shown that the proposed method allows the driver's habits to be taken into account so that the location of road signs can be optimized. The observable effect was a reduction in vehicle speeds and speed variance on critical road segments, translating directly into increased safety and harmonized traffic.

INDEX TERMS Optimal traffic control, variable speed limits (VSL), vehicle speed variance.

I. INTRODUCTION

Variable speed limits (VSL) supports intelligent transportation system (ITS) solution in traffic management [1]. The idea is to propose speed limits to drivers in response to incidents or current (or predicted) traffic conditions, weather, or road surface conditions. Currently, the typical implementation of VSL is using Variable Message Signs (VMS) installed on the side of the road or over the road.

The primary goal of introducing VSL is to improve traffic safety (i.e., to reduce the number of accidents on a given road segment) and traffic efficiency (i.e., to reduce congestion, prevent or discharge traffic jams, and decrease the time of travel) [2]. Understandably, safety is usually the top priority, and there are several ways to reduce the probability of accidents and victims using VSL:

- adjusting speed limits to the current or predicted traffic conditions (e.g., traffic density) to ensure a safe distance
- adjusting speed limits to the current or predicted weather and road surface conditions (e.g., rain, snow, fog, road slippery)
- adjusting speed limits to harmonize traffic - reduce the number of accelerations, decelerations, lane changes, and overtaking
- adapting speed limits in case of detected incidents

Problems related to motorway entrances require the most effective possible solution for connecting a large traffic stream with several streams of much lower volume. The most commonly described traffic control strategies include ramp metering, variable speed limits (VSL), and route guidance. Among ramp metering, the Asservissement Lineaire d'Entrée Autoroutiere (ALINEA) strategy has gained popularity [3], [4].

The rapid increase in traffic has caused many problems in cities and motorways, but on the other hand, it has stimulated innovation in the search for solutions. Some of them use state-of-the-art technologies, such as the Internet of Things and the Mobile Internet, to predict the trajectory of vehicles using deep multi-scale machine learning, thus creating highly accurate traffic models [5]. Although phenomena of this magnitude are not the subject of this article, the idea of using such a seemingly remote phenomenon as radio device trajectories is a good inspiration, especially since the VSL road signs we constructed have this capability [6].

The associate editor coordinating the review of this manuscript and approving it for publication was Shaohua Wan.

Installing signs on roads with a straight, linear geometry is not a difficult task. Installing them on winding roads with tight curves is considerably more challenging regarding the selection of displayed speed. Determining the optimal sign location requires an analysis of traffic conditions and road geometry. Acceptable, safe vehicle speeds on curves must be determined, taking into account the varying, weather-dependent properties of the road surface, driving comfort, and driver's behavior. Establishing a road sign distance from the start of a road curve, determined solely based on braking distance, can result in vehicles entering the turn at a too-high speed.

On the other hand, an excessive distance may cause drivers to become irritated and speed up, with the abovementioned effect. This phenomenon does not necessarily always provoke accidents (as long as vehicles do not skid). Still, it is usually associated with excessive, uncomfortable centripetal acceleration, which is detrimental and negatively impacts driving safety.

Research carried out in the late 1980s [7] showed that another phenomenon that increases the risk of collisions is excessive speed variance. An identified factor affecting speed variability is the difference between the design speed of the road and the posted speed limit. Research has shown that the speed variance will be minimal if the speed limit is between 10 and 19 km/h lower than the design speed. Beyond this range, the speed variance increases as the difference between the design speed and the speed limit increases. Drivers tend to travel at increasing speeds as the geometric characteristics of the carriageway improve, regardless of the posted speed limit. An important and interesting result of the study is that the number of accidents does not necessarily increase with an increase in average speed but increases with an increase in speed variability, i.e., as the vehicle speed varies from the average speed on the road [7]. The conclusions presented in [7] have also been partially confirmed in recent studies. The increase in collision risk caused by driving at a speed higher than that of other road users was considered. In opposition to older studies, the finding of increased collision risk due to slower driving is inconclusive [8].

The article attempts to answer the following questions:

- does the location of VSL signs affect the parameters that determine traffic safety? In this case, the parameter of interest is the speed variance that translates into safety.
- does the variability of vehicle speed has a minimum depending on the location of VSL signs?

The experiments were conducted on a two-lane local road. This non-urban road has a maximum speed limit of 90 km/h. The road has an irregular course with numerous curves, including one with an angle of 180 degrees. It was chosen for the study because its course and location can facilitate the subsequent verification of the results obtained by computer simulation in real conditions. The results indicate that the method makes it relatively easy to analyze forecast traffic and driver behavior in different road sign foundation configurations and select the optimal design. The choice of the simulator is not critical. The Vissim traffic simulator ([9]) was used to carry out the research described below, and the Wiedemann 74 model was used as the traffic model. Since the variance of vehicle speeds is for long time considered an essential road safety parameter [3], the authors of this paper decided to analyze it to determine to what extent it is affected by VSL distance distribution.

The contribution of our article can be summarized as follows:

- assuming the influence of VSL signs location (distribution of distances from each other) on the traffic speed variance,
- verifying the above assumption by computer simulation of several configurations of a test road section configurations in the Vissim environment.

The rest of this paper is organized as follows: Section II contains a brief review of the literature, Section III describes the experiment, Section IV - presents experimental results, Section V includes a discussion of the results, and Section VI presents conclusions.

II. RELATED WORK

Variable Speed Limits are not an entirely new traffic control method; many approaches and algorithms already exist in the scientific literature [2]. However, real-world implementations of VSL are still not widespread. Still, some successful examples of deployments exist, and it was already experimentally proved that VSL can improve traffic safety. For instance, in the UK, the VSL system reduced injury accidents by 15%; the decreased stop-and-go traffic during peak hours and decrease in duration and a number of breakdowns indicate a more harmonized traffic [2], [10]. There are also systems implemented in, e.g., the Netherlands, Sweden, and Germany, where it was also proved that VSL gives better traffic harmonization or a lower number of accidents [2], [11], [12]. The already completed ETC-VSL project under the HORIZON 2020 framework carried out by the European Commission should also be mentioned here. Among the results of this project was the development of a practical variable speed limit (VSL) control strategy for recurrent traffic jams [13], a new macroscopic variable speed limit model [14], and a new macroscopic highway VSL model [15].

Probably for the first time, an analytical formulation of the problem of optimal location of variable speed areas was presented in [16]. Therefore, the results presented in the above publication may help establish practical guidelines for the VSL control strategy.

An interesting implementation of a rule-based VSL controller is presented in another paper [13]. Online optimization is not necessary for this solution, which seems to be a significant advantage.

Besides the field tests, a direct way to study VSL systems is by using traffic simulation, and there are numerous such studies [2], [17], [18], [19]. Their conclusions are similar:

VSL can harmonize traffic, reduce the number of rapid speed changes and lane changes, and improve safety, as a consequence.

An appropriately designed speed recommendation algorithm can significantly impact the minimum distance between vehicles, affecting traffic safety [20]. In addition, a properly selected number and location of VSL signs can reduce substantially congestion tendencies and travel times [20].

However, some studies also show that VSL may be inefficient in case of large traffic density, which should also be considered. Similar conclusions cannot be generalized, as some publications have presented large-scale, accurate models and scenarios built on the open-source SUMO program [21]. Another example of a successful implementation of a VSL system for heavy traffic is presented in the literature [22].

Combining results from specialized programs is common to deepen conclusions, e.g., traffic signal optimization obtained with Synchro with microscopic simulation in Sumo [23].

Complex and in-depth studies use actual measurement data to build and calibrate motion models, which are then used in microscopic simulation in a program such as Sumo, supported by an external computational program, most commonly Matlab [3], [24].

Most existing algorithms, studies, and deployments focus on straight-road segments without bends and curvatures. The goal of considered VSLs is usually traffic harmonization, i.e., to reduce the number of rapid speed changes, lane changes, and overtaking. They typically try to harmonize speed on different lanes, and in case of congestion, they also try to reduce the speed limit upstream to delay the flow of new vehicles. However, they rarely consider changing weather conditions (e.g., visibility) and road surface conditions, which are also sometimes difficult to measure. However, this factor seems to be a significant cause of car accidents. For example, more than 5.8 million motor vehicle accidents occur annually in the United States, and around 23 percent are weather-related [25]. Some theoretical studies consider cooperative VSL with vehicle-to-infrastructure as a promising approach.

The Regional Development Fund subsidized a project entitled: "INZNAK (INSIGN): Intelligent Road Signs with V2X Interface for Adaptive Traffic Controlling," which was completed in 2021 with the participation of the authors of this paper. The project resulted in prototypes of autonomous traffic signs capable of displaying the recommended driving speed [6].

The approach was conceived as a step toward filling in the gap of insufficient research regarding the application of VSL in adverse weather conditions, combining VSL control adapting to traffic conditions, road surface conditions, and sharp bends simultaneously. We continue to look for methods to automatically select the speed displayed on these autonomous traffic signs, which is the reason for the research presented in this paper.

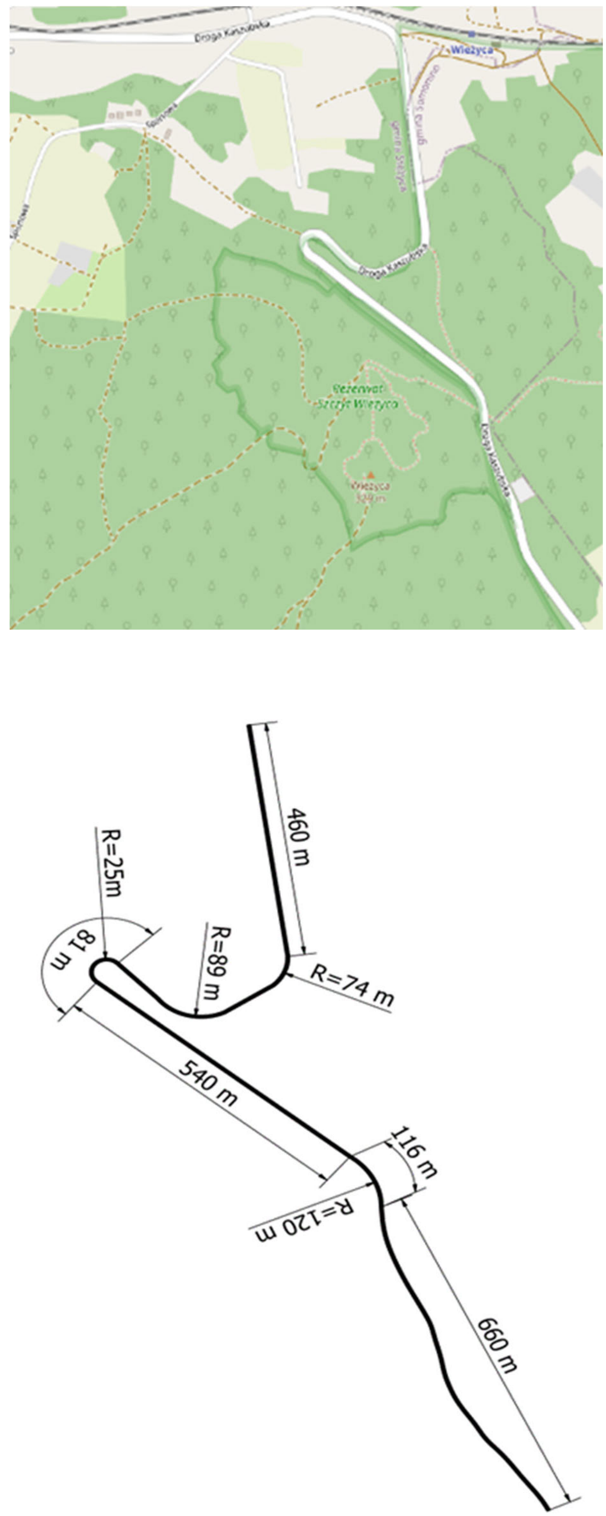

FIGURE 1. Road network from the considered simulation scenario.

III. MATERIAL AND METHODS

A simulation scenario on a two-way local, non-urban road segment with two lanes in the northern part of Poland was prepared to run experiments and validate the developed method (Fig. 1).

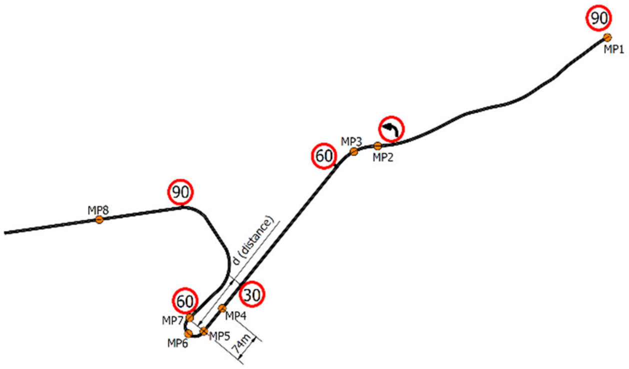

FIGURE 2. The location of the speed limit signs and measuring points.

The considered segment had a length of about 2.3 kilometers and consisted of primarily straight parts with several bends. The location of the speed limit signs and measuring points are shown in Fig. 2.

The maximum speed limit is 90 km/h, and the traffic volume did not exceed 380 v/h. According to the Polish road directorate, 95% of the traffic consists of cars and 5% of trucks. These are the values used in the simulation. In the experiments, we only considered the free flow of vehicles. Such quantities, in principle, prevent the need to consider mechanisms such as platooning. Still, in the more general case, it would be necessary to consider both the observed propensity of vehicles to form groups and the strategies that exploit this phenomenon [26], [27].

According to [28], a change in speed of more than 20 km/h is in the group of "poor designs"; however, in Poland, the regulations allow such a change if the design speed does not exceed 90 km/h, which is the case in question.

A significant problem is the calibration of the model used for the simulation. As stated above, the Wiedemann 74 model was used, which is represented by equation (1):

$$\mathrm{ABX} = \mathrm{AX} + (\mathrm{bx_{add}} + \mathrm{bx_{mult}}N)\sqrt{V} \tag{1}$$

where:

ABX - is the minimum desired following distance

AX - is the average standstill distance

$\mathrm{bx_{add}}$ - is the additive part of safety distance

$\mathrm{bx_{mult-}}$ is the multiplicative part of safety distance

N - is a value of range [0.1], which is normally distributed around 0.5 with a standard deviation of 0.15 [29]

V - is the vehicle speed in m/s

As actual data for the test section was not available, the default values (and also suggested in the literature [29], [30]) were adopted:

AX $= 2$ m

$\mathrm{bx_{add}} = 2$ m

$\mathrm{bx_{mult}} = 3$ m

$N = 0.5$

It is assumed that the speed is uniformly decelerated in the case of braking. However, the deceleration constant depends on the weather and road conditions, such as slippery, curvature, or steepness, and it should not exceed a maximum allowing to brake without skidding. Furthermore, in normal traffic conditions, the deceleration should not exceed what is considered comfortable.

It is also assumed that, for most drivers, a deceleration greater than about 3.4 m/s^2 is experienced as uncomfortable. Therefore, AASHTO recommends taking this value for calculations [31]. However, it should be noted that different values are reported in the literature, e.g., studies described in [32] indicate a value of 1.357 m/s^2, those described in [33] 2.87 m/s^2, and given in [34] 0.85 m/s^2. Since the Vissim simulator was used for the simulations, the acceptable default value, according to [35], is 3.0 m/s^2 for cars and 1.5 m/s^2 for trucks. Therefore, the latter factor, i.e., 1.5 m/s^2, was adopted in further calculations.

Assuming deceleration a has a constant value, the distance traveled by the vehicle when changing speed from V_0 to V_1 can be described by the equation:

$$d = V_0 t_r + \frac{V_0^2 - V_1^2}{2a} \tag{2}$$

where t_r is the driver's response time according to [31], it can be assumed that $t_r = 2.5$s.

For convenience so that that speeds can be given in km/h, (2) can be transformed into the form:

$$d = 0.278 V_0 t_r + 0.039 \frac{V_0^2 - V_1^2}{2a} \tag{3}$$

The value of a in both equations is given in m/s2.

The above equations apply only to movement along a trajectory located on the horizontal plane, sufficient to illustrate the method.

The basic equation that governs vehicle operation on a curve is [31]:

$$f + 0.01e = \frac{V^2}{127R} \tag{4}$$

where: V = vehicle speed in km/h

f = side friction

e = rate of roadway superelevation, percent

R = radius of curve measured to a vehicle center of gravity, in [m].

From (4), one can obtain the following value of vehicle speed:

$$V = \sqrt{127R(f + 0.01e)} \tag{5}$$

As the exact path parameters, i.e., e and f, were not known, the values suggested in [31] were used for further considerations:

- $e = 6\%$
- $(0.01e + f) = 0.34$

and, from (4), maximum speed on a curve with a radius of 25 m and dry pavements: $V = 33$ km/h.

The second parameter limiting vehicle speed on a curve is the acceptable value of the centrifugal reaction (b_{acc}):

$$V = \sqrt{127R(\frac{b_{acc}}{g} + 0.01e)} \tag{6}$$

The value of b_{acc} is speed-dependent and decreases with increasing speed. It has been the subject of many studies and analyzes. Surprisingly, the values found in the literature are so divergent. According to the literature [36], b_{acc} should be taken from the range of 0.4..1.3 m/s^2. According to [31], this value is about 2.4 m/s^2 for speeds of 30 km/h. The authors of articles [36] and [37] give a discomfort limit of 2.6 m/s^2 and 5 m/s^2, respectively (for speeds of 40-50 km/h). Since the values reported by AASHTO [31] were determined based on studies conducted in the 1930 s of the 20th century, there are suggestions in the literature to adapt them to modern realities. Recent studies- suggest higher values, e.g., in [37]. As it is not the purpose of this article to argue on this subject, for further discussion, it has been assumed that $b_{acc} = 3$ m/s^2. From eq. (6), we then obtain $V = 34$ km/h.

In this case, we obtained very close values, so a limit of 30 km/h for dry pavement was assumed.

For an initial value of $V_0 = 60$ km/h, a final value of $V_1 = 30$ km/h, and a deceleration of $a = 1.5$ m/s^2 (for heavy goods vehicles), (3) yields a distance between the speed limit sign and the beginning of the road curve of 77 m.

The friction available on most wet pavement surfaces and the capabilities of most vehicle braking systems can provide braking friction that exceeds the deceleration rate of 3.4 m/s^2 [31].

For the case of a slippery carriageway, the coefficient of friction is assumed to be $f = 0.15$. Equation (5) then gives V= 25.6 km/h. The speed limits (Fig. 2) were changed for this case from 30 km/h to 25 km/h and from 60 km/h to 50 km/h.

The experiment purpose was to check the dependence of the variance of vehicle speeds on the controlled road section on the location of speed limit signs and the distance between them. As previously stated, studies confirm that both an increase in speed and an increase in the variance of vehicle speeds cause a significant increase in accidents [8]. For this reason, the variability of vehicle speed is an important parameter, and the search for methods to reduce it is most justified.

The results will form the basis for developing a control algorithm for autonomous variable message traffic signs. The research was designed as a series of experiments involving traffic simulation on the road shown in Fig. 2. The parameters recorded were vehicle speeds, accelerations, distances between vehicles, and driving time. The experiments were conducted for three distances d: 75 m, 100 m, and 150 m, and for two pavement conditions: dry and icy. All scenarios assumed a simulation resolution of 20 time steps per each simulation second (i.e., 0.05 s) and a simulation duration of three hours. The processing of the data obtained from the simulation and the calculations were performed in the R language environment.

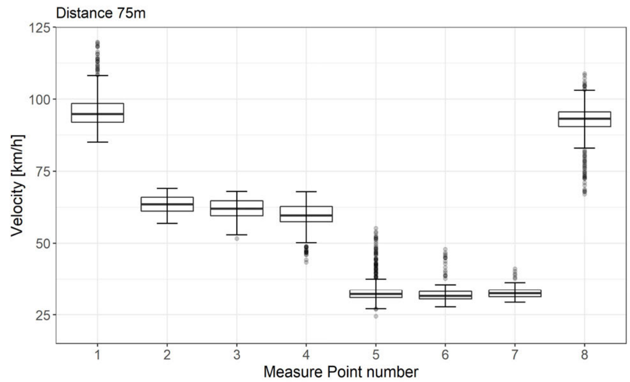

FIGURE 3. Vehicle speeds for d =75m. A relatively high proportion of vehicles travel at too high a speed when entering a bend (outliers of measurement point 5). At pt. 6 (half the length of the road curve), there are noticeably fewer clusters, and it doesn't appear important at the end of the curve.

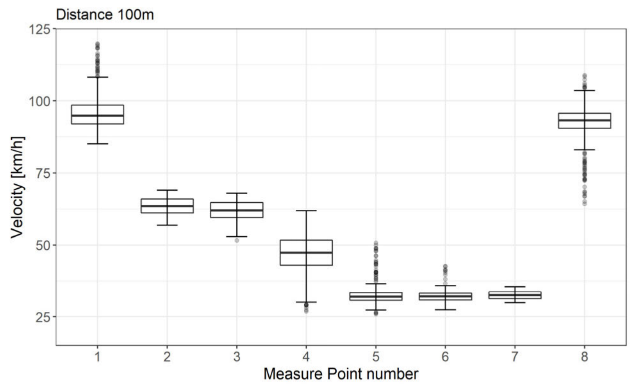

FIGURE 4. Vehicle speeds for d = 100m. There are noticeably fewer vehicles traveling at too high a speed when entering the bend (outliers of measurement point 5) than in Fig. 3, similarly in the middle and at the end of the bend.

IV. RESULTS

The first part of the results presented is for dry pavement. However, as the critical element of the road shown in Fig. 2 is a sharp bend, the main focus will be on the data acquired from survey points 5 (start of road curve), 6 (middle of road curve), and 7 (end of road curve).

Fig. 3, 4, and 5 show the speeds of the vehicles at the measurement points for the distance above configurations, marked 'd' in Fig. 2

It can be seen in Fig. 3 that vehicle speeds when entering a bend have a significant variance, and a group of vehicles enters the bend at too high a speed.

This group constitutes the outliers at measuring point 5. On the other hand, point 6 (half the length of the road curve) is related to a noticeably less numerous cluster and appears negligible at the end of the curve. able

The speed variance for the slippery case is shown in Fig. 16.

V. DISCUSSION

The location of the road signs has a clear impact on driver behavior. The distance corresponding to the distance theoretically needed for lorries to reduce speed, which is usually

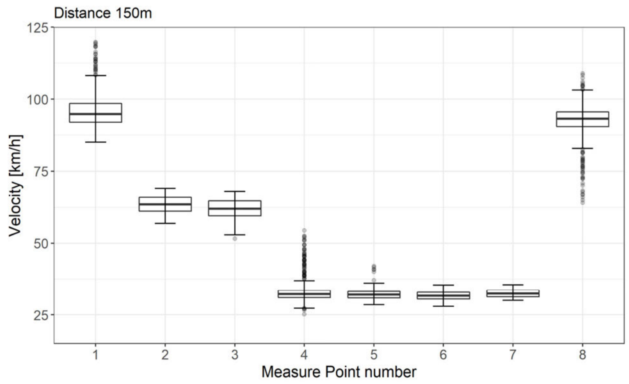

FIGURE 5. Vehicle speeds for d = 150m. Only a slight trace of vehicles traveling at too high speed is visible when entering a bend (outliers -measuring point 5). This phenomenon no longer occurs in the middle (measuring point 6) and at the end of the bend (measuring point 7).

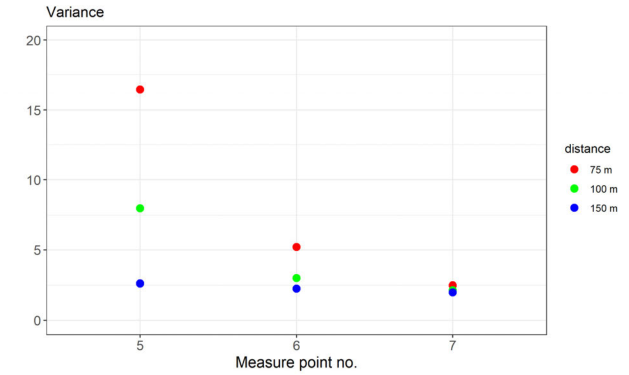

FIGURE 6. Speed variance on a road curve (measuring points 5, 6, and 7), dry pavement case. At the starting point of the curve (measuring point 5), an apparent decrease in variance can be observed with an increase in distance *d*. In the middle of the bend, the relationship is much weaker and practically invisible at the end of the road curve (measuring point 7).

sufficient for passenger cars, seems too short. Fig. 5, measurement point 5, shows that a relatively large group of drivers enter the bend at too high a speed. The 85% percentile value shown in the figure is 34.5 km/h. An additional negative phenomenon is the large speed variance at the beginning of the curve (still measuring point 5).

Increasing the distance to 100m brought a clear improvement, i.e., a reduction in speed at the start of the curve and a reduction in speed variance.

A distance of 150 m appears to be close to optimal. The initial speed (measuring point 5 in Fig. 5) is lower than in both previous configurations. The variance difference at measurement points 5 and 7 is the smallest (Fig. 6). Based on Fig. 6 and 16, it can be assumed the variance reaches a minimum if its values are determined at the extreme points of Fig. 6 and 16, i.e., points 5 and 7, are the same. It should also be noted that in all cases, a very small proportion of the vehicles traveled at the recommended speed or less, as seen in Fig. 5, 6, and 7. Another observation is that distance *d* impacts speed and speed variance at the beginning of the road curve. The influence is less in the middle of the curve, while at the end,

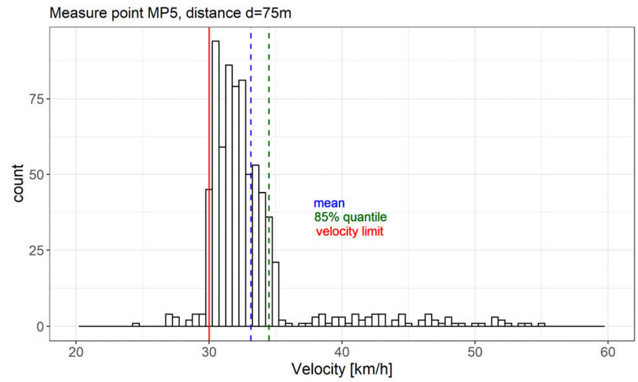

FIGURE 7. Distribution of vehicle speeds at measuring points MP5 and distance d = 75m. There is a visible group of vehicles exceeding the 85% quantile speed.

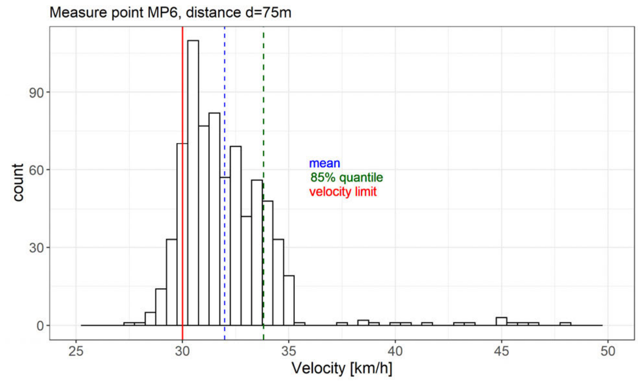

FIGURE 8. Distribution of vehicle speeds at measuring points MP6 and distance *d* = 75m. Both the number of vehicles traveling too fast and the maximum measured speed are lower than in Fig. 7.

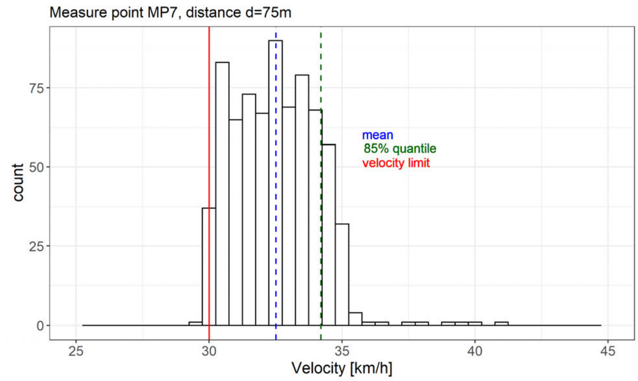

FIGURE 9. Distribution of vehicle speeds at measuring points MP7 and distance *d* = 75m. Both the number of vehicles traveling too fast and the maximum measured speed are lower than in Fig. 7 and 8.

the effect is practically invisible. Interestingly, all vehicles start to accelerate, but the speed variance at measuring point 7 is the smallest and most common to all configurations (Fig. 4).

In the case of slippery pavement and the change of speed limits from 60km/h to 50km/h and from 30km/h to 25km/h, the results are less satisfactory. The reduction in speed on the

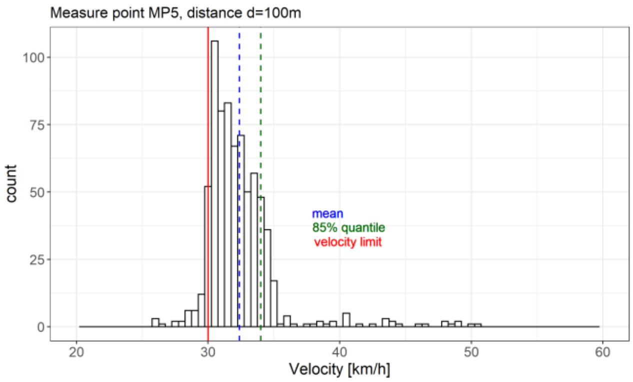

FIGURE 10. **Distribution of vehicle speeds at measuring points MP5 and distance d = 100m. The effect of increasing the distance d is apparent. Both the number of vehicles traveling too fast and the maximum measured speed are lower than in Fig. 7, i.e., at the same measuring point.**

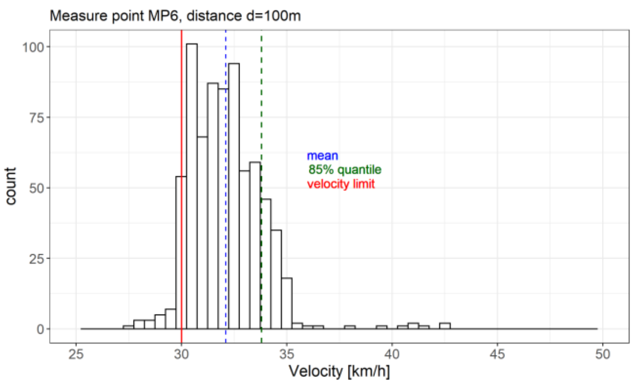

FIGURE 11. **Distribution of vehicle speeds at measuring points MP6 and distance *d* = 100m. The impact of increasing the distance d is still visible, although not as significant as at the entrance of the turn. Both the number of vehicles traveling too fast and the maximum measured speed are lower than in Fig. 8, i.e., at the same measuring point.**

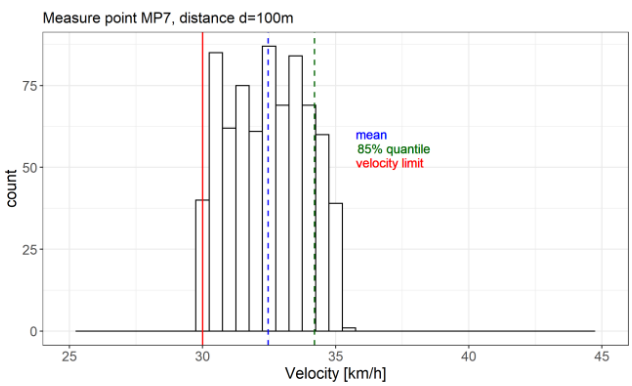

FIGURE 12. **Distribution of vehicle speeds at measuring points MP7 and distance d = 100m. The impact of increasing the distance d is still apparent, although not as significant as at the entrance of the bend. Both the number of vehicles going too fast and the maximum measured speed are lower than in Fig. 9, i.e., at the same measuring point.**

road curve is noticeable but insignificant. The speed variance, however, turned out to be higher.

More detailed comments are provided in the captions of Fig. 3-15. The above results apply to a specific configuration, so any attempt to change the distance between road signs in practice would require recalculated simulations.

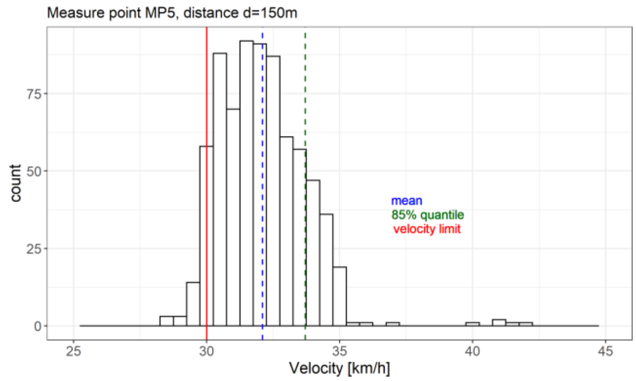

FIGURE 13. **Distribution of vehicle speeds at measuring points MP5 and distance d = 150m. The number of vehicles traveling too fast and the maximum measured speed is lower than in Figs. 7 and 10, i.e., at the same measuring point.**

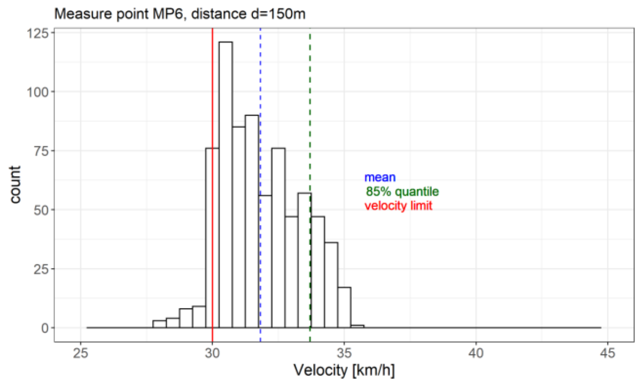

FIGURE 14. **Distribution of vehicle speeds at measuring points MP6 and distance *d* = 150m. The speed variance is lower than at measuring point 5 (Fig. 13).**

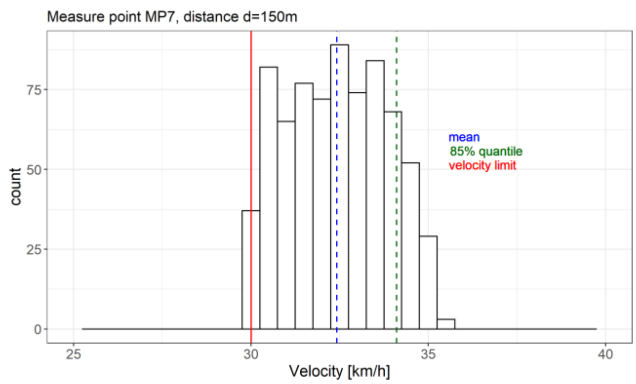

FIGURE 15. **Distribution of vehicle speeds at measuring points MP7 and distance *d* = 155m. The variance in speed is minimal.**

It would also be interesting to compare the results obtained for two different models of driver behavior, i.e., the Wiedermann model and the Intelligent Driver Model (IDM), as presented in the publication [36].

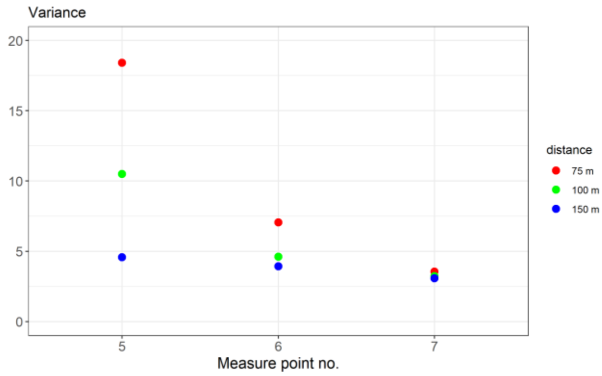

FIGURE 16. Variance of vehicle velocity for distance d equals 75m, 100m, 150m (slippery pavement case). The speed variance at the beginning and middle of the road curve is noticeably higher than for dry pavement (Fig. 6). the speed limits at the preceding points are likely suboptimal.

VI. CONCLUSION

The presented study investigated the effect of the distance between VSL road signs on the variability of vehicle speed. The results show that the distance distribution between road signs considerably influences vehicle speed variability. Therefore, by appropriately configuring the location of VSL road signs, the variability of vehicle speed can be preliminarily reduced, thereby increasing traffic safety. The research was conducted with an autonomous and adaptive traffic control system in mind because the development of smart traffic signs inspired it.

The observations were made using computer simulations, which may be an advantage in practice, as changes and experiments using this approach inherently do not cause actual traffic obstructions. Consequently, the authors, involved in constructing advanced VSL road signs, assumed their distribution design method might find its way into practical applications.

ACKNOWLEDGMENT

The authors would like to acknowledge Paweł Gora's input in the pre-publication version of this article, from which they used excerpts from the literature analysis.

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