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Effects of highway work zone temporary countermeasures

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Abstract

Highway work zones are associated with significant adverse impacts on safety. Mitigating these impacts can be achieved by implementing several countermeasures. This paper uses controlled experiments in a driving simulator to investigate the effects of physical and digital temporary traffic control countermeasures on work zone safety. These include variable message signs, dynamic speed displays, rumble strips, and lane widths. 116 participants were recruited for the experiment. A linear mixed-effects model was developed to capture the effects of these countermeasures on average travel speed and standard deviation of speeds in the advanced warning area and within the work zone itself. The results reveal that rumble strips installed within the work zone cause the strongest reduction in speeds. Narrower lanes cause smaller speed reductions. In general, the effects of temporary traffic control countermeasures on speeds were local and were not retained beyond their proximity.

Keywords Highway work zone, Safety countermeasures, Driving simulator, Variable message sign, Dynamic speed display, Rumble strips

1 Introduction

Highway work zones (HWZ) are usually accompanied by an increase in the risk of traffic crashes [1–3]. The literature offers several Temporary Traffic Control (TTC) countermeasures to mitigate the elevated risks in the HWZ. These countermeasures can be grouped into three categories: (i) physical TTC to alert drivers, such as rumble strips; (ii) digital TTC that provides information to drivers, such as Dynamic Speed Display (DSD) and Variable Message Sign (VMS); and (iii) presence of flaggers and police patrol. The effects of these countermeasures on safety are commonly approximated through their effect on speed and speed variance. Speeding is a major cause of road crashes in HWZs [4, 5]. Large speed variance is also a contributing factor to road crashes [4, 6–9].

Rumble strips alert drivers by causing vibration and audible rumbling. Several field studies evaluated their safety benefits alone or with other countermeasures. The literature shows that rumble strips significantly affect vehicle speeds [10]. Fontaine and Carlson [11] observed reductions in the mean speed of 3.2 km/h and 11.5 km/h for passenger cars and trucks, respectively. Sun et al. [12] found an increase of more than 10% in the number of vehicles that braked and an increase of 2.9% in speed compliance. Wang et al. [13] found that rumble strips could create 12.2 to 17.0 km/h speed reductions if set properly. In all these studies rumble strips were installed at the advanced warning area (AWA), upstream of the work zone itself. Data collection instruments were installed upstream of the AWA as a reference point and at points downstream of the rumble strips, but still within the AWA.

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VMSs convey information on traffic conditions, such as congestion, road crashes, road closures, alternative route, and work zones. Several studies evaluated the effect of VMS information messages in the AWA. In a field study, Zech et al. [14] found that the message content affects the speed and speed variance. The most effective combinations of messages reduced average speeds by 5.3–10.8 km/h, but increased speed variance. In driving simulator experiments, Wang and Cao [15] found that drivers responded faster to VMS that displayed discrete messages, single-line messages, and when driving on the outer lane.

DSDs alert drivers of their current speed and compare it with the posted maximum speed limit. Several field studies investigated their effect on speed compliance. Mccoy et al. [16] found that they reduce average speeds on interstate HWZs by 6–8 km/h. Benekohal et al. [17] examined the effect of HWZ DSDs at the place where they are installed in the AWA, and at a point 2.4 km downstream within the work zone itself. The reduction in average speed in the AWA was between 5.1 and 11.7 km/h for both cars and heavy vehicles. Smaller reductions were measured in the work zone itself. There was no significant reduction for cars whereas heavy vehicles reduced speed between 1.4 and 4.0 km/h. Cruzado and Donnell [18] found a reduction of 10 km/h in average free-flow speeds on the AWAs of two-lane, rural highway work zones.

HWZs are usually accompanied by narrower lanes, which lead to lower free-flow speeds [19] and more so in HWZs [20]. Lastly, flaggers and police presence mitigate HWZ risks by providing drivers with clear rules and managing traffic. However, they come with a substantial increase in project cost.

The impacts of TTC on speeds and safety may be evaluated using crash records and field studies. While these methods rely on naturalistic data, it is difficult to isolate the effects of the various factors. Field studies may also be expensive and risky, whereas crash records are often incomplete and inaccurate. Driving simulator studies provide a useful alternative. They are low-cost and avoid potential risks associated with real-life situations. They can be used with controlled experiments that support the identification of the contributions of the various factors and can easily provide measurements over entire sections rather than at specific points. Their main disadvantage is limited realism: Driving simulator experiments do not fully mimic real-life experiences (e.g., sound, car rumbling) and do not carry the same consequences of crashes or traffic violations. Several studies evaluated their validity. For example, no statistical difference in speed was found between the simulator and the real world [21, 22]. Bham et al. [23] showed similar results and also that experiment participants found the simulator environment realistic. Melo et al. [24] found that speeds measured in a driving simulator are significantly higher than those observed in the real-world. However, these biases were systematic, and so the differences in speeds between different conditions, and the distributions of speeds recorded in the driving simulator were valid. Therefore, they concluded that simulator data can be used to indicate on expected field impacts of various factors.

In summary, the literature shows that the effects of various countermeasures, including rumble strips, VMS, and DSD were evaluated at specific point locations, mostly in the AWA. The results of these studies show wide ranges of impacts on speeds, which may be attributed to multiple uncontrolled factors, such as the exact measurement location, road type and annual average daily traffic. Thus, evaluation in controlled experiments is needed.

To help overcome these limitations, this study evaluates the effects of work zone countermeasures on speed and speed variance over the entire work zone including both the AWA and within the work zone itself in a controlled experiment using a driving simulator. The simulator also allows measuring the effects continuously over the entire section rather than only at specific points. The focus of this study is on physical and digital countermeasures that are characterized by relatively low costs. The countermeasures studied are rumble strips, DSDs, and VMSs in addition to lane narrowing. In the experiments, the subjects' speeds were collected at a high time resolution. The data was used to estimate Linear Mixed-Effects Models (LMEM) that capture the effect of the countermeasures on speed and standard deviation of speed, which have been often used in the literature as surrogate safety measures (see [25] for a review).

2 Experiment

2.1 Simulator

A STISIM Drive [26] simulator, located at the Technion – Israel Institute of Technology, was used in the study. It is a fixed-base medium-level PC-based simulator, which includes a steering unit, brake and throttle pedals and a sound system. The 60° horizontal by 40° vertical scene display is projected on three screens, as shown in Fig. 1. The refresh rate is 30 frames per second. The simulator supports introducing vibration to the steering wheel and noise to more realistically simulate passing of rumble strips. As noted above, the simulator has been validated extensively as a tool to measure driving performance and behavior (see also [27] for a review).

2.2 Experiment design

The participants drove through a sequence of HWZs and the AWAs that precede them on a two-lane two-way inter-urban road. Each set of AWA and HWZ sections

Fig. 1 STISIM driving simulator environment

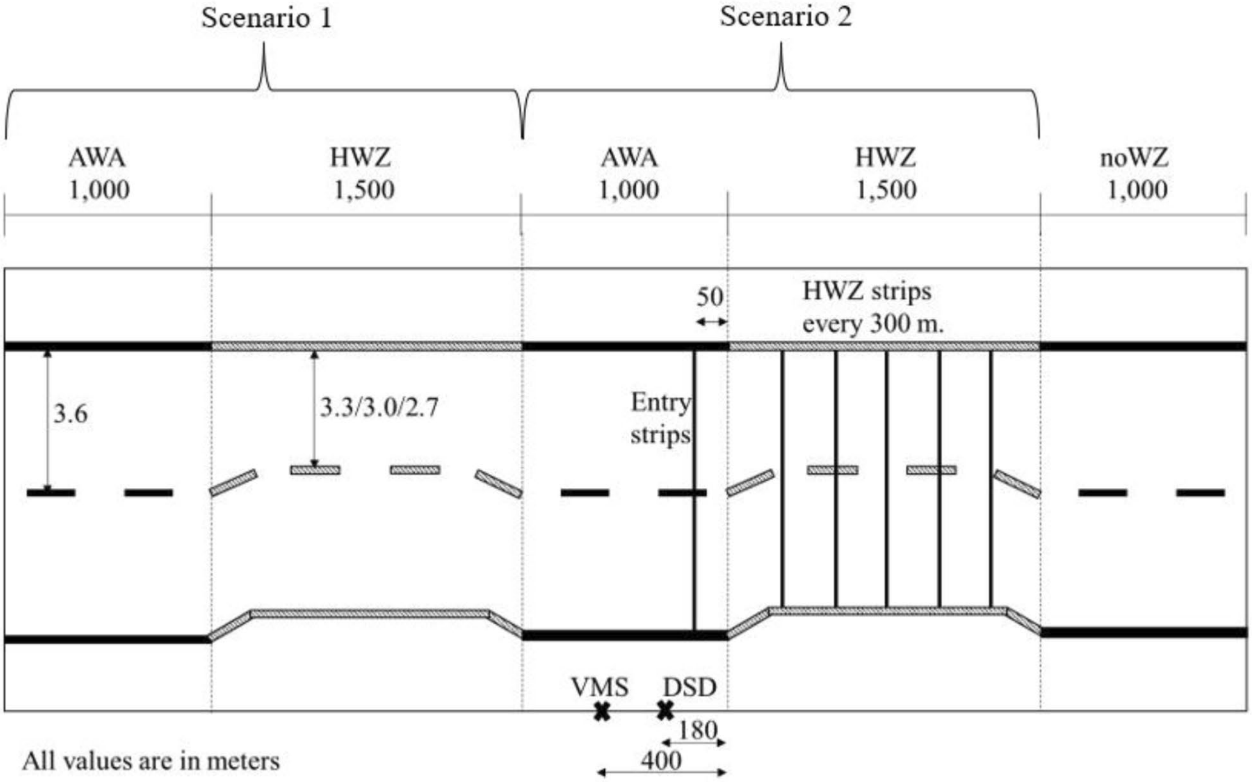

Fig. 2 Road layout for a driving simulator run

constitute a scenario. In total, each participant drove through eight scenarios. To reduce participants' fatigue and boredom, the scenarios were arranged in four simulator runs (containing two scenarios each) with a short break between them. Each run included driving 6 km, which in addition to the two scenarios included a final section without any work (noWZ), as shown in Fig. 2. The design of the 1.5-km long HWZ sections included the transition, activity, and termination areas, as mandated by their design guidelines. The AWA and noWZ sections were 1-km long each. Road works were executed on the right shoulder causing lane narrowing. Lane widths in the AWAs and noWZ sections were 3.60 m. Depending on the experimental scenario, they were reduced to either 3.30, 3.00, or 2.70 m in the HWZ. There were no other differences in the road geometry between the AWA, HWZ and noWZ sections. Left and right shoulders were 1.8 m each. The posted speed limit was 90 km/h. It was reduced to 70 km/h in the HWZ. Daytime conditions were applied in all runs.

Two separate experiments were conducted with the driving simulator: Experiment 1 focused on the physical countermeasures: rumble strips and lane widths. No VMS or DSD were present in this experiment. Experiment 2 focused on these two digital countermeasures. It also included variations in the lane width, which were found relevant in the first experiment. The possible values of these factors in the two experiments are listed in Table 1.

In each one of the two experiments, a full factorial design, with all possible combinations of the factors listed in Table 1 was applied to define the scenarios. This resulted in eight possible scenarios for Experiment 1 and twelve for Experiment 2. In both experiments, each participant drove through eight scenarios. For Experiment 1 this means that participants drove through all the scenarios. To account for the possible effect of their order, an 8×8 Latin square was constructed for Experiment 1. Participants in Experiment 2 did not drive all scenarios. An 8×12 Latin rectangular was constructed to control both scenario selection and ordering. As described above, the eight scenarios that each participant drove through were arranged in four simulator runs.

The installation locations of rumble strips in Experiment 1 and of VMS and DSD in Experiment 2 are also shown in Fig. 2. Entry rumble strips were installed 50 m upstream of the HWZ. HWZ rumble strips were installed throughout the HWZ at 300-meters intervals. In the simulator, driving over rumble strips generated vibration of the driving wheel and a rumbling noise to mimic real-life experience. VMSs were located on the right shoulder in the AWA, 400 m upstream of the HWZ. They rotated between two messages that were shown for one second each: “SLOW DOWN” and “WORK ZONE AHEAD”. DSDs were located on the right shoulder in the AWA, 180 m upstream of the HWZ. They showed the vehicle’s current speed and the 70 km/h maximum speed limit of HWZ.

Table 1 Countermeasures and their possible values

Countermeasure	Experiment 1	Experiment 2
Entry rumble strips	With, Without	Without
HWZ rumble strips	With, Without	Without
VMS	Without	With, Without
DSD	Without	With, Without
HWZ lane width (m.)	3.3, 3.0	3.3, 3.0, 2.7
Number of scenarios (Full factorial)	8	12

2.3 Procedure

After initial registration and consent form signing, participants were briefly introduced to the driving simulator and were given a 3-km trial drive to familiarize themselves with it. They were instructed to drive as they would normally do in the real world. Then, they drove four simulator runs, which were randomly assigned to them. Each run took 4–7 min to complete. A one-minute break was given between runs. After the driving task, the participants completed a personal information questionnaire.

The measures of performance used in both experiments were average speed and standard deviation. They were calculated separately for each AWA, HWZ and noWZ section, resulting in 20 data points for each participant. The average and standard deviations of speeds are calculated from instantaneous speed measurements taken every 0.1 s resolution.

2.4 Participants

Forty-six and seventy participants completed Experiment 1 and Experiment 2, respectively. A participant could take part only in one of the two experiments. They were students and staff members recruited on the Technion campus using billboards and announcements in social networks. Participation in the experiment was voluntary. The participants were not compensated for their effort. The results of six of the participants (one in Experiment 1 and five in Experiment 2) were excluded from the analysis due to technical problems or since they were judged to not drive sincerely. Therefore, the total number of subjects was 110, 70 males and 40 females. Age ranged from 20 to 79 years old with an average age of 28.5 years and a standard deviation of 11.9 years. The number of years of driving experience ranged from 1 to 49 years with an average of 10.3 years and a standard deviation of 10.6 years. None of the participants exhibited signs of driving sickness.

3 Modelling approach

3.1 Data

The data used as dependent variables in the analysis were the average and standard deviation of speed in each section, which have been shown to be associated with road crashes. As noted above, each participant completed four simulator runs with five sections (two AWAs, two HWZ and one noWZ) in each run. Four of the participants had only three valid runs due to technical issues. Therefore, there were a total of 2,180 observations that were used for modeling. The average speed of all measurement points for all participants was 84.3 km/h (23.4 m/sec) with a standard deviation of 18.7 km/h (5.2 m/sec).

The explanatory variables that were considered are listed in Table 2. The effects of VMS, DSD, and entry rumble strips were tested on the AWA (where they were

Table 2 Independent variables and their possible values

Independent variables	Possible values
VMS	With, Without
DSD	With, Without
Entry rumble strips	With, Without
HWZ rumble strips	With, Without
Lane width	3.30, 3.00, 2.70 m
Road section	AWA, HWZ, noWZ
Run order	1, 2, 3, 4
Age	20–24, 25–29, Over 30 years old
Gender	Male, Female
Experiment	1, 2

installed) and the HWZ that follows it. The position of a run within the sequence of four runs that a participant drove is included to correct for changes over time in the driving performance that may occur due to learning of the driving task, fatigue or boredom, which may bias the results. The age variable was discretized into three categories, rather than considering it as a continuous variable. The relations between driver' age and crash rates, speed selection and other driving behaviors has been shown to be nonlinear (e.g., [28, 29]). The specific categories used in the model (ages 20–24, 25–30, over 30) were selected after experimentation with different definitions and numbers of categories. The selected categories provided the best model fit. There were 69, 22 and 19 participants in the 20–24, 25–30 and over 30 age groups, respectively. Including the age group variables in the model corrects for their effects, and therefore the imbalance in the group sizes does not bias the results.

3.2 Linear mixed Effect Model (LMEM)

An LMEM [30] was used to capture the effect of the countermeasures used in the experiments on speed and speed standard deviation. This model structure captures both fixed and potentially correlated random effects:

$$\begin{aligned} In(y_{ij}) &= \beta_0 + \beta_1 X_{ij1} + \cdots + \beta_m X_{ijm} \\ &+ \eta_{i1} X_{ij1} + \cdots + \eta_{im} X_{ijm} + \varepsilon_{ij} \end{aligned} \quad (1)$$

$$\eta_i \sim N(0, \Omega);\ {}_{ij} \sim N(0, \sigma^2)$$

Where the indices *i*, *j* and *m* signify participants, observations (the twenty measurement points of each participant) and factors, respectively. y_{ij} is the dependent variable value. X_{ijm} is the value of factor for that observation. $\beta_0 \ldots \beta_m$ are the fixed effect parameters. η_{im} are normally distributed subject random effects. Ω is their $(m+1)\,x(m+1)$ variance-covariance matrix. ϵ_{ij} is a normally distributed error term with variance σ^2. η_i and ϵ_{ij} are independent of each other and identically distributed among the subjects.

Two LMEM were developed with average speed and the speed standard deviation as dependent variables. In the model development process, various specifications were estimated and compared based on the Akaike Information Criteria (AIC) values. Following the guidance Zuur et al. [30] the maximum likelihood method was used for model selection. The final models were estimated using restricted maximum likelihood. The linear mixed model's function in SPSS statistics v28 [31] was used in all cases.

The model development process addressed several specification questions: First, four separate models for the average speed and standard deviation models in each experiment (1 and 2) were estimated. Then the data of the two experiments were combined to estimate joint models. For both average speed and speed standard deviation, the AIC value for the joint model was larger than the sum of AICs for the two corresponding separate models. Therefore, the joint model was retained. Within this model, the usefulness of individually differing the effects of the various factors between the two experiments was tested. The only differentiation that significantly improved the model's likelihood value, and therefore kept in the final model, was for the effect of the HWZ in the speed variance model. Finally, different specifications in terms of the factors for which random effects were included and the variance-covariance structures of these effects were tested. The final speed model includes random effects for the intercept (for each participant), run order, and HWZ strips. The final speed standard deviation model includes random effects for the intercept, AWA, and HWZ. For completeness of the discussion, the results presented in the next section show two models for each of the two dependent variables: A full model that includes all the countermeasures that were used in the experiments, and a final parsimonious model that only includes those that significantly affected the dependent variables.

4 Results and discussion

As noted above, several variance-covariance structures (Ω) were examined for the random factors included in the model. Table 3 presents the results for three error structures: diagonal (uncorrelated random effects), first-order autoregressive with homogenous variance, which captures correlations due to the repeated measurements for the same individual, and fully unconstrained. The autoregressive models provide small improvements over the models that do not incorporate these temporal effects but are substantially inferior to the ones with unconstrained random effects. It should be noted that the model specifications presented later include the run order as explanatory variables, which already capture

Table 3 Log-Likelihoods and number of parameters with various covariance structures

Covariance Structure		Unconstrained	Autoregressive	Diagonal
Speed - Full	Log likelihood	1804.62	1751.87	1746.49
	Parameters	35	22	25
	AIC	-3539.24	-3459.74	-3442.97
Speed - Parsimonious	Log likelihood	1802.28	1747.36	1743.67
	Parameters	29	16	19
	AIC	-3546.56	-3462.72	-3449.34
Speed Variance - Full	Log likelihood	-1897.58	-1907.45	-1907.50
	Parameters	27	23	24
	AIC	3849.16	3860.90	3862.99
Speed Variance - Parsimonious	Log likelihood	-1901.82	-1913.71	-1913.53
	Parameters	19	15	16
	AIC	3841.64	3857.43	3859.06

some of the serial effects. Based on these, the unconstrained covariance structure was selected.

Table 4 show the estimation results and confidence intervals (CI) for the average speed model with this error structure. To help interpret the estimated model, Fig. 3 shows the expected and CIs of percentage changes in the average speed predicted by changes in the explanatory variables.

The results in Table 4; Fig. 3 show reduced speed choices in the AWA and HWZ. Speeds in these zones are lower by 4.9% and 11.7% respectively, relative to the noWZ section. Among the physical countermeasures evaluated, narrower lanes resulted in lower speeds. Consistent with the work zone design guidelines, lanes are narrowed in all the simulated HWZ sections. This means that their effect is confounded with that of the HWZ itself. Therefore, in the model, the lane width of 3.30 m is used as a base and the coefficients of the other lane widths are interpreted as additional change in speed in the HWZ compared to this base. A lane width of 3.00 m in the HWZ reduced the speed in this section by 1.1% compared to a width of 3.30 m. Narrower lanes of 2.70 m, reduced the speed in the HWZ by 1.8%. Entry rumble strips were installed in the AWA, 50 m upstream of the beginning of the work zone. They had a small, statistically insignificant effect on speeds in the AWA where they were installed. This effect became even smaller in the HWZ. Thus, the effect of entry rumble strips is only local and relatively small. Therefore, these effects were not kept in the final model. HWZ rumble strips, which were installed at regular intervals along the entire HWZ, had a much stronger and sustained effect – reducing speeds by 5.4%. The effects of digital countermeasures on speeds were more limited. The effects of DSD were negligible both in the AWA, where they were installed, and in the following HWZ. VMS reduced speeds in the AWA by 3.5%. But this effect did not carry over to the HWZ.

In terms of demographics, males drove faster than females, and younger drivers faster than older ones. The run variables capture the effect of the order in which participants undertook the runs. The results consistently show that participants drove faster in the later runs. Possible explanations are that a learning process improved the familiarity with the driving task over time or that increased boredom with the driving task motivated faster speeds for faster completion of the experiment.

The random parameters in the model capture inter-individual differences in speed. Enabling heterogeneity of the effects among the subjects allows to identify the mean effects more accurately. The choice of variables that were included with random effects was not made a priori. It was dictated by the data, as the combination of variables that provided best model fit in terms of AIC. The results show that there is significant variability in the base speed selected by the participants and in how it evolves between the various runs. That is, the increase in speed over runs varied for different participants, which may be caused by different learning rates and levels of interest in the simulator driving task among participants. Among the TTCs, rumble strips in the HWZ were the only factor that significantly improved the model when their effect was specified as random. This may be partly explained by differences in drivers' desired speeds over rumble strips. This heterogeneity may be magnified in the simulator experiment, which represents the noise and vibration caused by rumble strips but not the dynamics of the vehicle's movement over it.

A useful observation from the results reported above is that countermeasures that were installed at a single point (i.e., entry rumble strips, VMS and DSD) did not have substantial effects over the entire HWZ or AWA. Thus, it was examined whether they had more localized effects immediately before and after the points where they were installed. Figure 4 shows the local effects of speed for DSD, VMS, and entry rumble strips relative to their respective installation point. In all three cases, the impact on speed peaked shortly downstream of their installation point and diminished quickly further downstream.

Table 4 LMEM Estimation results for average speed (m/sec) model

	Full model				Parsimonious model			
Fixed effects	**Est. Value**	**Std. Error**	**p-value**	**95% CI**	**Est. Value**	**Std. Error**	**p-value**	**95% CI**
Intercept	3.230	0.034	< 0.001	[3.163, 3.297]	3.195	0.025	< 0.001	[3.146, 3.244]
Experiment 2	-0.047	0.032	0.148	[-0.110, 0.016]	-	-	-	-
AWA	-0.047	0.006	< 0.001	[-0.059, -0.035]	-0.050	0.006	< 0.001	[-0.062, -0.038]
HWZ	-0.123	0.008	< 0.001	[-0.139, -0.107]	-0.125	0.007	< 0.001	[-0.139, -0.111]
Lane width 3.00	-0.011	0.007	0.125	[-0.025, 0.003]	-0.011	0.007	0.128	[-0.025, 0.003]
Lane width 2.70	-0.018	0.009	0.050	[-0.036, 0.000]	-0.018	0.009	0.041	[-0.036, 0.000]
Entry strips - AWA	-0.014	0.009	0.132	[-0.032, 0.004]	-	-	-	-
Entry strips - HWZ	-0.008	0.009	0.358	[-0.026, 0.010]	-	-	-	-
HWZ rumble strips	-0.058	0.012	< 0.001	[-0.082, -0.034]	-0.056	0.012	< 0.001	[-0.080, -0.032]
DSD in AWA	0.003	0.008	0.739	[-0.013, 0.019]	-	-	-	-
DSD in HWZ	0.001	0.008	0.902	[-0.015, 0.017]	-	-	-	-
VMS in AWA	-0.038	0.008	< 0.001	[-0.054, -0.022]	-0.036	0.007	< 0.001	[-0.050, -0.022]
VMS in HWZ	-0.001	0.008	0.865	[-0.017, 0.015]	-	-	-	-
Male	0.050	0.028	0.079	[-0.005, 0.105]	0.048	0.028	0.089	[-0.007, 0.103]
Age 25–29	-0.072	0.032	0.024	[-0.135, -0.009]	-0.067	0.032	0.038	[-0.130, -0.004]
Age over 30	-0.208	0.042	< 0.001	[-0.290, -0.126]	-0.174	0.036	< 0.001	[-0.245, -0.103]
Run 2	0.036	0.009	< 0.001	[0.018, 0.054]	0.036	0.009	< 0.001	[0.018, 0.054]
Run 3	0.053	0.011	< 0.001	[0.031, 0.075]	0.053	0.011	< 0.001	[0.031, 0.075]
Run 4	0.062	0.012	< 0.001	[0.038, 0.086]	0.062	0.012	< 0.001	[0.038, 0.086]
Random effects								
Residual	0.008	0.0003			0.008	0.0003		
σ_1^2 (Intercept)	0.018	0.003			0.018	0.003		
σ_2^2 (Run2)	0.007	0.001			0.007	0.001		
σ_3^2 (Run3)	0.009	0.002			0.009	0.002		
σ_4^2 (Run4)	0.012	0.002			0.012	0.002		
σ_5^2 (HWZ strips)	0.003	0.001			0.003	0.001		
ρ_{12}	0.124	0.125			0.108	0.124		
ρ_{13}	0.122	0.120			0.104	0.119		
ρ_{23}	0.769	0.064			0.774	0.063		
ρ_{14}	0.133	0.117			0.132	0.117		
ρ_{24}	0.725	0.070			0.728	0.069		
ρ_{34}	0.816	0.051			0.818	0.051		
ρ_{15}	-0.007	0.207			-0.059	0.202		
ρ_{25}	0.032	0.269			0.041	0.268		
ρ_{35}	-0.188	0.239			-0.169	0.238		
ρ_{45}	-0.301	0.219			-0.285	0.219		

Among them, VMS impacted speeds the most, both in terms of the magnitude of speed reduction and the length of the area that its effect was sustained.

The standard deviations that were modeled next are for the intra-individual speeds, i.e. reflect the variability of speed of the same driver within the various zones. Tanishita and Wee [32] have shown that these are related to increasing crash risks. The speed standard deviation model results are presented in Table 5; Fig. 5. They show large differences among the zones: speed variability increases substantially in both the AWA (by 20.9%) and HWZ (by 22.3%) compared to the noWZ section. The variable HWZ – Experiment 2 is an interaction variable of the HWZ section and Experiment 2. Its coefficient is positive and significant. It indicates that the speed variability in the HWZ in Experiment 2 was 21.8% greater than in experiment 1. This was the only experiment-specific variable that significantly improved the model. Lane widths did not significantly affect the speed variability. Entry rumble strips increased speed variability on the AWA by 13.5%. However, this effect was only local near the point where they were located and did not carry over to the HWZ. HWZ rumble strips significantly increased the speed variability as drivers decelerate when approaching them and accelerate after passing them.

The variables related to the digital countermeasures that affected speed variability are similar to the ones that affected the average speeds. The directions of effects are opposite. Variables that were associated with higher average speeds are also associated with lower speed

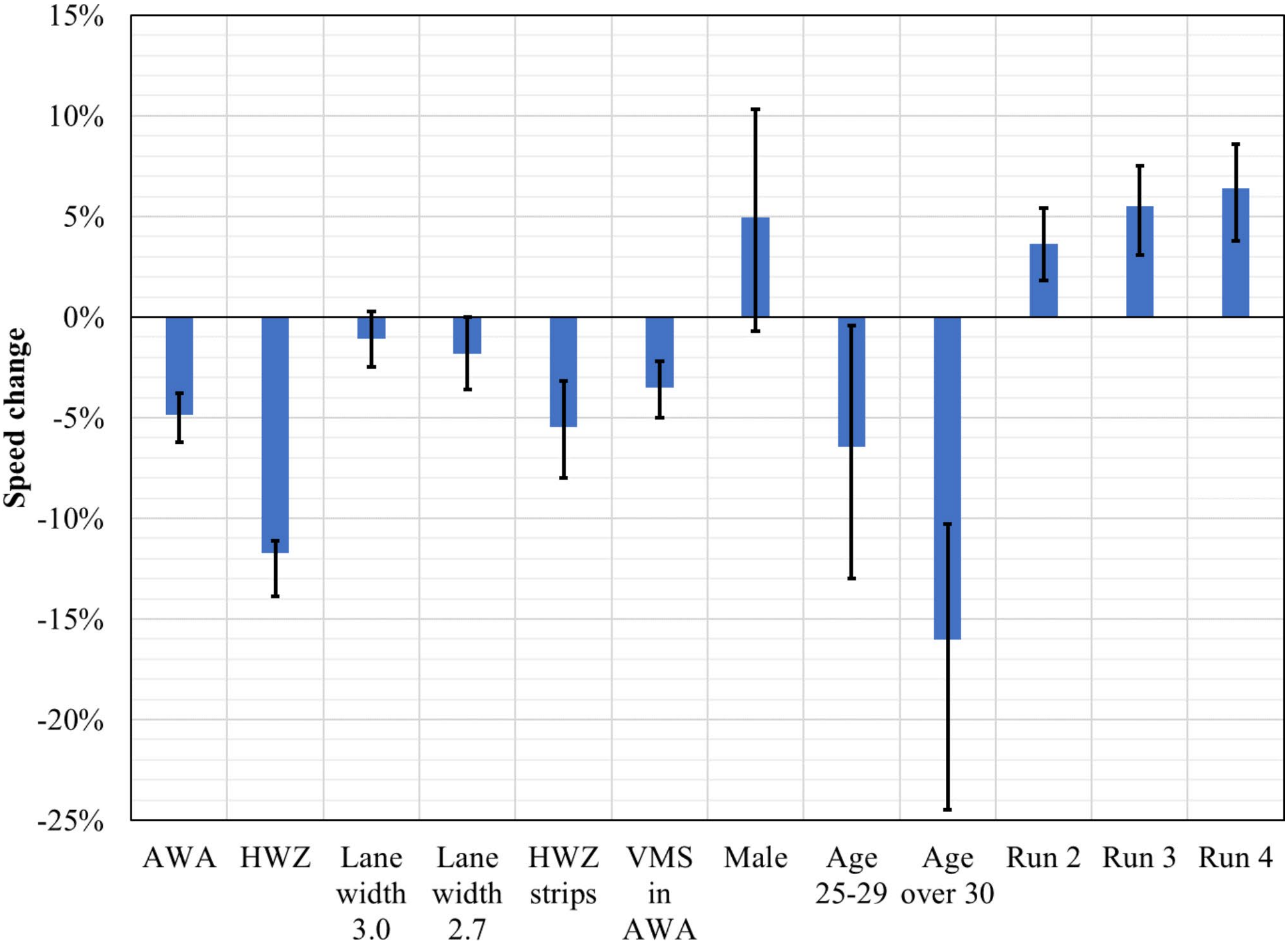

Fig. 3 Average Speed change (%) associated with the explanatory variables

variability, and vice versa. In both models the effect of DSD is small and insignificant. The effect of VMS is larger, and increases speed variability (where is at had a negative effect on the average speed). But, similar to the effect on average speeds, it is limited to the AWA where it is installed.

The speed variability was lower for male drivers and for older drivers, in the 30 years or older group. As with the average speed model, the run order also affected the standard deviation of speed. The direction of effect is that speed variability decreased for later runs. As with the increase in average speed in later runs, it is plausible that this effect is related to both participants' learning process of the simulator driving task and boredom or indifference to it.

The random effects part of the model shows larger inter-individual differences in speed standard deviations in the AWA and HWZ. These areas are characterized by changes in the road geometry and the presence of TTCs. Drivers need to react and change their speeds in response to these changes. Different drivers may be interpreting the situations in these areas differently, and so reacting with different sensitivities and at different times, which affects their speed variances. This heterogeneity in response among drivers may be a contributing factor to increased risk in the HWZ.

5 Conclusions

Controlled experiments in a driving simulator were conducted to investigate the safety effects of physical and digital TTC countermeasures that are characterized by low costs as means to mitigate crash risks at HWZs. The physical TTC countermeasures considered were rumble strips at the entry to the work zone or at regular intervals within it and lane narrowing. The digital TTC countermeasures were VMS and DSD.

Previous studies investigated the effect of these and similar countermeasures only at the AWA and using point measurements of vehicle speeds. Their results varied substantially with respect to the effects on speeds. This may be explained in part by the use of point speeds, by differences in locations where these speeds were measured and by lack of control in field studies. The current study implemented controlled driving simulator

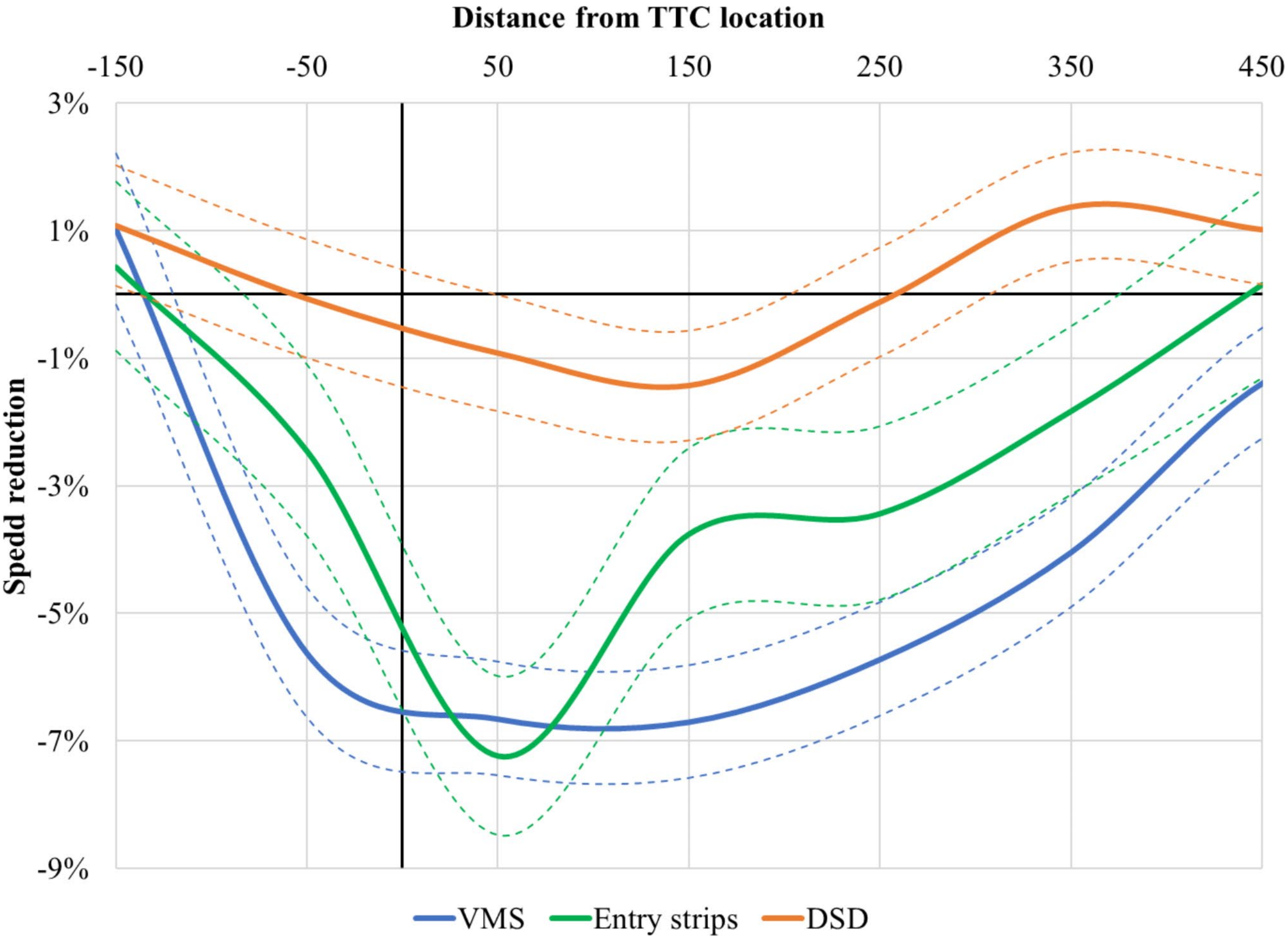

Fig. 4 Local effects of single point TTCs on average speed

experiments to investigate the effect of these countermeasures on speed and speed standard deviation over the entire AWA and HWZ sections. Thus, it provides a more complete view of driver's speed selection and variability along the entire work area.

LMEMs were developed to capture the TTC countermeasures' effects on average speeds and their standard deviations. The results revealed that the effects of point countermeasures (i.e., DSD, VMS, and entry rumble strips) are local, if at all, to the immediate vicinity of the points where they were installed in the AWA. They do not carry over to the HWZ itself. DSDs did not have any significant effect on the average or standard deviation of speed. Entry rumble strips and VMS had a small local effect. The speed reduction peaked shortly downstream of their installation point and faded quickly within 300–400 m. Only rumble strips that were installed at regular intervals over the entire work zone area affected speeds over the entire HWZ. Thus, the effects on speed of this type of TTC, which is physical and repeated over the entire HWZ, are more pronounced. However, their effects on the speed characteristics are in opposite directions: they decrease the average speed but increase its standard deviation. The implications on crash rates, which are expected to increase with both higher speeds and higher speed variability, are also contradictory. Therefore, the results are not conclusive with regard to the safety implications. This is the case also for the other TTCs. In all cases that TTCs affected the average speeds and the speed standard deviation, these effects were in opposite directions: they reduced average speeds, but increased intra-individual, and in the case of HWZ rumble strips also inter-individual, speed variability. The literature generally emphasizes the association of speed variability to crash risk over that of the average speed. Therefore, the results raise questions about the usefulness of the TTCs that were studied. Reduced speeds were also measured with narrower lanes.

Several limitations of the study need to be acknowledged. As noted above, an important advantage of driving simulator experiments is the ability to conduct controlled experiments, which allow to identify the effects of the various factors being studies. However, this comes at the cost of reduced validity of the results.

Table 5 LMEM Estimation results for the standard deviation of speed (m/sec) model

	Full model				**Parsimonious model**			
Fixed effects	Est. Value	Std. Error	p-value	95% CI	Est. Value	Std. Error	p-value	95% CI
Intercept	0.520	0.083	< 0.001	[0.357, 0.683]	0.428	0.063	< 0.001	[0.305, 0.551]
Experiment 2	-0.108	0.076	0.155	[-0.257, 0.041]	-	-	-	-
AWA	0.178	0.049	< 0.001	[0.082, 0.274]	0.190	0.048	0.001	[0.096, 0.284]
HWZ	0.130	0.076	0.090	[-0.019, 0.279]	0.201	0.066	0.003	[0.072, 0.330]
HWZ - Experiment 2	0.298	0.092	0.001	[0.118, 0.478]	0.197	0.074	0.009	[0.052, 0.342]
Lane width 3.00	0.043	0.041	0.297	[-0.037, 0.123]	-	-	-	-
Lane width 2.70	0.066	0.054	0.221	[-0.040, 0.172]	-	-	-	-
Entry strips - AWA	0.116	0.054	0.033	[0.010, 0.222]	0.127	0.052	0.015	[0.025, 0.229]
Entry strips - HWZ	0.056	0.057	0.323	[-0.056, 0.168]	-	-	-	-
HWZ rumble strips	0.195	0.057	0.001	[0.083, 0.307]	0.194	0.057	0.001	[0.082, 0.306]
DSD in AWA	0.038	0.046	0.413	[-0.052, 0.128]	-	-	-	-
DSD in HWZ	-0.035	0.048	0.469	[-0.129, 0.059]	-	-	-	-
VMS in AWA	0.162	0.046	< 0.001	[0.072, 0.252]	0.154	0.045	0.001	[0.066, 0.242]
VMS in HWZ	-0.065	0.048	0.172	[-0.159, 0.029]	-	-	-	-
Male	-0.156	0.058	0.009	[-0.270, -0.042]	-0.169	0.058	0.004	[-0.283, -0.055]
Age 25–29	-0.076	0.066	0.249	[-0.205, 0.053]	-	-	-	-
Age over 30	-0.294	0.088	0.001	[-0.466, -0.122]	-0.213	0.074	0.005	[-0.358, -0.068]
Run 2	-0.011	0.032	0.739	[-0.074, 0.052]	-0.010	0.032	0.752	[-0.073, 0.053]
Run 3	-0.077	0.032	0.017	[-0.140, -0.014]	-0.077	0.032	0.017	[-0.140, -0.014]
Run 4	-0.104	0.032	0.001	[-0.167, -0.041]	-0.104	0.032	0.001	[-0.167, -0.041]
Random effects								
Residual	0.284	0.009			0.285	0.009		
σ_1^2 (Intercept)	0.133	0.028			0.142	0.029		
σ_2^2 (AWA)	0.102	0.029			0.105	0.029		
σ_3^2 (HWZ)	0.098	0.028			0.099	0.028		
ρ_{12}	-0.699	0.085			-0.721	0.077		
ρ_{13}	-0.487	0.124			-0.492	0.121		
ρ_{23}	0.545	0.134			0.561	0.130		

Drivers' behavior in the simulator, speed choices in this case, may differ from what they would apply in the real-world due to the limited realism of the scenarios, absence of any crash risk or other consequences of their driving decisions, or indifference to the simulator driving task. Thus, support from field data would be useful to ascertain (or disprove) the results. The sample of participants in the experiments is not representative. Participants are disproportionally young students, as they were recruited at the Technion campus. The models that were specified attempt to overcome this by accounting for differences among age groups, but not for education levels or other characteristics. Additional experiments with larger, more diverse socio-demographic participants would be needed to strengthen the validity of the results also in this respect. Finally, the measures of performance used in the study were speed and its variability. These have been shown to be associated with crash risk, and commonly used as safety indicators. While these may be readily calculated in simulator experiments, they do not fully capture the effects of the various countermeasures on safety. Furthermore, the results suggest that the various TTC affect the average speed and its standard deviation in opposite directions. However, crash risk is positively associated with both indicators. Therefore, the results are inconclusive about the overall effect on safety. In future research it would be useful if the findings could be corroborated with field data, from a variety of locations, that include both information on the deployment of TTCs and on traffic flow characteristics and crash records.

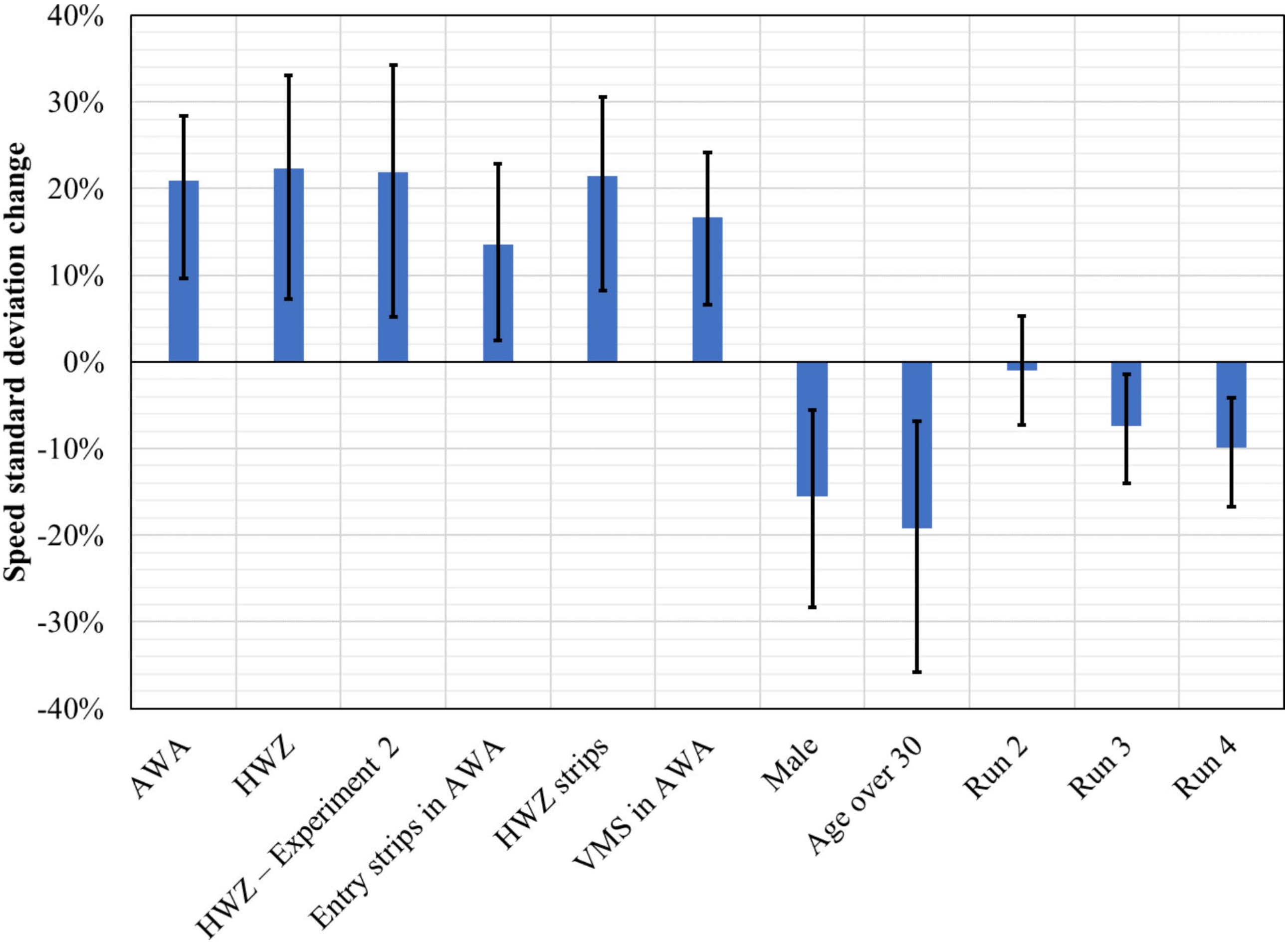

Fig. 5 Speed standard deviation change (%) associated with the explanatory variables

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Authors' contributions
Fadi Shahin: Conceptualization, Methodology, Software, Formal analysis, Data Curation, Writing - Original Draft, Visualization. Wafa Elias: Conceptualization, Methodology, Writing - Review & Editing, Supervision. Tomer Toledo: Conceptualization, Methodology, Software, Formal analysis, Data Curation, Writing - Review & Editing, Supervision.

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The datasets used and analyzed during the current study are available from the corresponding author upon reasonable request.

Declarations

Competing interests
Not applicable.

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