Sandstorm animations on rural expressways: The impact of variable message sign strategies on driver behavior in low visibility conditions

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Sandstorm animations on rural expressways: the impact of variable message sign strategies on driver behavior in low visibility conditions

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Problem: Evolving sandstorms on rural expressways in desert countries impair drivers' contrast vision and increase the risk of serious crashes due to delayed speed adjustments. Intelligent Transport Systems (ITS) such as Variable Message Signs (VMS) conveying warnings can be activated to address drivers' speed adaptation before entering a low visibility zone. To improve drivers' understanding of the hazard, a sandstorm animation visualizing turbulent sand and its consequences was designed and compared with a general warning pictogram, which is applied if no specific weather pictogram is available. Moreover, minimum warning distances of the VMS to the low visibility zone were tested (e.g., 300 m or 500 m). *Method:* Sixty-three participants from the State of Qatar drove in a driving simulator through clear, transition, and low visibility conditions on a rural expressway. A repeated analysis of variances was conducted to examine the impact of the two on-road warning displays on driving behavior. *Results:* The results showed that the sandstorm animation was similarly effective as a generic warning pictogram in reducing driving speeds before entering the transition and low visibility zone, irrespective of being displayed 500 m or 300 m away. However, the sandstorm animation resulted in consistent similar speed reductions within the low visibility zone, whereas the generic warning pictogram did either perform better or worse after several encounters with a sandstorm. Drivers did strongly agree that the animation is clearly referring to the issue of low visibility, which can be beneficial for recurring low visibility conditions. *Practical applications:* 1.) Displaying a sandstorm animation is beneficial for rural expressway sections with recurring degrading visibility and low traffic densities, whereas a warning pictogram can be more effective in speed reductions if drivers expect additional traffic hazards. 2.) Roadway authorities have the flexibility to activate a VMS sandstorm warning even for minimum warning distances.

Keywords*:* display design; adverse weather; minimum warning distance; speed reduction; driving simulator

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1. Introduction

Traffic safety on desert expressways does not receive much attention in the literature although unusual high crash rates are found in desert regions (Ismutulla, Xin & Xiao-song, 2008). Studies from Saudi Arabia (Islam et al., 2019) and Kuwait (Al-hemoud et al., 2019) confirm that road crash casualties due to sandstorms pose significant indirect costs to the country. Moreover, a recent study from Qatar highlighted that most of the severe injury and fatal road traffic crashes occur during changing seasons, which are characterized by strong winds, fog, and dust haze (Civil Aviation Authority Qatar, 2018; Timmermans et al., 2019). In particular, the sandy environment along the rural desert expressway affects drivers' safety due to a decline in dynamic vision. A Chinese study showed that drivers' speed estimation and reaction times were more impaired on the Taklamakan desert expressway than the average national expressway, which was reflected by a higher number of driving errors (Ismutulla et al., 2009). A sandstorm is a reoccurring weather phenomenon in desert countries around the world that causes widespread and heavy dust deposition and low visibility. Typically, fine particles are transported through the wind and deposit as dust clouds affecting, in particular, the rural segments of expressways (Wang, 2015). Sand- and dust storms are defined as severe if the air is extremely turbid reducing horizontal visibility to below 50 m (Cao et al., 2018). In these circumstances, a driver's ability to see and respond to roadway hazards is impaired and crashes are more likely to occur.

Various studies have been conducted to investigate the impact of reduced visibility in several weather conditions on driving behavior (Chang et al., 2019; Jeihani & Banerjee, 2019; MacCarley et al., 2006; Wu et al., 2018). These studies usually focus on the effect of fog and heavy rain impacting visibility. Significant effects on drivers' speed control, as well as deceleration and lane-keeping variations were found, which increase the risk for run-off or multiple car crashes (Das, Ghasemzadeh, & Ahmed, 2019). However, studies that investigated the impact of reduced visibility caused by sandstorms are very scarce (Ismutulla et al., 2008, 2009; Lin et al., 2005). In particular, literature concerning pre-warning systems for impaired visibility due to sandstorms lack, although strong winds and low visibility increase the chance of road crashes on rural expressways (Shepherd et al., 2016). Furthermore, the diversity of drivers with different cultural backgrounds and safety attitudes, on the one hand, and the lack of experience in driving in sandstorm conditions among expatriate drivers, on the other hand, aggravates the problem. A large variety of international expatriates are temporarily living in the State of Qatar, which contributes to a heterogeneous composition of drivers on the roads. More than 90% of the general driving population is non-Qatari and, in many cases, neither able to communicate in Arabic nor English (Ghadban et al., 2018; Soliman et al., 2018; Timmermans et al., 2019; 2020). This raises many challenges to road authorities in terms of identifying the most effective approaches to warn drivers of changing visibility conditions. A potentially promising approach could be the use of Intelligent Transport Systems (ITS), which can provide warnings through effective display designs of Variable Message Signs (VMS). It is aimed to warn and prepare international travelers of the adverse driving conditions caused by low visibility due to sandstorms or related weather conditions that endanger safe driving on rural expressways. On the one hand, VMS can display the same coding schemes and graphics that are usually displayed on static signs. On the other hand, new display designs can be developed that might be more effective in facilitating the comprehension of information (Castro & Horberry, 2004). Therefore, this study is initiated to identify and examine the effectiveness of VMS warning designs on driving behaviors before sandstorm induced low visibility.

1.1. Low visibility

As already mentioned, research on the possible mitigation strategies to address driving behavior before sandstorm induced low visibility is almost nonexistent. Notwithstanding, useful insights can be derived from research on countermeasures for related climatological or weather conditions that are known to reduce visibility. There is, for instance, a clear parallel between sandstorm conditions (i.e., dust particles in the air), and fog (i.e., water vapor in the surface air). Sándor (2017) studied the effect of reduced visibility and showed that drivers did not reduce speed or change behavior until the visibility was severely impacted (i.e. 150 ft or 45 m visibility distance). It was found that most drivers were still driving at speeds where they could not stop safely anymore in case of a hazard (Sándor, 2017), which is also confirmed by other studies (Brooks et al., 2011; Yan et al., 2014). Several studies that used driving simulators (Jeihani & Banerjee, 2019; Wu, Abdel-Aty, Park, & Selby, 2018; Yan et al., 2014) or on-road traffic data (MacCarley et al., 2006) confirmed that drivers don't adapt their behavior if the fog level is moderate, indicating that drivers' speed adjustments were only affected by the low visibility levels below 45 m. Broughton, Switzer, & Scott (2007) tested dense fog conditions of 41 m to investigate drivers' car following decisions and found that driving under fog creates two groups of drivers who either tend to lag behind other vehicles or choose independently their speed (non-laggers). Also, MacCarley et al.'s (2006) expressway data showed that the potential collision speed increased since drivers tend to show platooning behavior with minimum following distance. Furthermore, Rosey et al. (2017) and Brooks et al. (2011) tested hazardous fog conditions of only 30 m visibility levels to investigate drivers' perception for appropriate speeds within the low visibility area. It can be concluded that drivers want to maintain higher driving speeds even under low visibility conditions. Safe driving behavior should be targeted by warning drivers of the consequences of unexpected vision degradation at a road section ahead.

1.2. Warning implementation

Various warning approaches have already been described and tested in the literature concerning fog. For example, Wu et al. (2018) conducted a driving simulator study to test roadside VMS with a warning and advisory message as well as beacons to influence drivers' speed reduction when entering a fog-affected road section. The results showed that in the beacon scenario, drivers were able to decelerate earlier before entering the fog. The VMS influenced drivers' braking behavior at the beginning of the reduced visibility zone, however, it did not influence the speed reduction proportion in the fog zone itself (Wu et al., 2018). Another driving simulator research was conducted to compare a freeway VMS with an advisory message, an on-board unit warning, and no fog warning when drivers were entering a heavy fog area (Chang et al., 2019). The findings of this study indicate that the VMS warning, which was implemented 500 m upstream of the fog zone, generally reduced drivers' speed before reaching the low visibility zone as compared to the scenario without a warning. Besides, the onboard unit warning affected the individual speed reduction (Chang et al., 2019). Another driving simulator study (Zhao et al., 2019) investigated the effectiveness of variable speed limits and fog warnings on driving behavior through the application of connected vehicle systems before entering the foggy condition. The fog warnings were displayed every 500 m and drivers' speed adjustments were analyzed within the clear zone, transition zone, and the fog zone. The tested visibility levels varied between no fog, slight fog, and heavy fog. The authors found that the in-vehicle warnings were effectively reducing drivers' travel speeds in all three impact zones and that it was also more effective in heavy fog conditions than in light fog conditions (Zhao et al., 2019).

MacCarley et al. (2006) studied the effect of a fog warning and speed instruction message on speed and deceleration of expressway vehicles for two years. In that study, the VMS was located 800 m before the fog monitoring station. During one fog season, the VMS was displaying different messages for two levels of visibility, whereas in another season, only one standard message was displayed. The results were compared with drivers' natural speed adjustments for fog visibility below 30.5 m (<100 ft). They found that the standard deviation of speed was not significantly influenced by visibility or VMS status. Besides, the drivers continued at mean speeds consistently above 97 km/h (>60 mph), even when visibility was very low. The authors have also pointed out that in case the issued warning was misaligned with the actual fog condition after 800 m, the perceived message relevance decreased (MacCarley et al., 2006). The message activation and distance to the actual event seem to affect the message-event contingency (i.e. the extent to which message recipients see a link between the warning message itself and the event warned for). The latter is to a very important extent determined by the distance/time separating the location where the warning is issued from the event warned for (e.g., MacCarley et al., 2006; Reinolsmann et al., 2018; Wu et al., 2018). Cooper & Sawyer (2005) tested the impact of a fog warning system on the driving behavior on expressways in England. Drivers were informed at least 800 m before the affected fog area through a VMS. The fog was detected by 54 detectors along the expressway. The authors found that the average speed collected at 300 m after the VMS was reduced by 2.9 km/h, and particularly, faster vehicles slowed down more than the average driver when the fog warnings were shown. The data collection at 300 m after the VMS is in line with guidelines for advance placement of warning signs, which generally recommend a minimum distance of 300 m for potential stop situations at a driving speed of >120 km/h (Federal Highway Administration, 2000). Also, existing guidelines for the location and installation of VMS suggest that gantry-mounted VMS should not be located at less than 300 m before the point where driving conditions change (Margison, 2008). This has been confirmed by a technical report suggest VMS installation and activation in the areas just before the fog zone or even into the pre-fog area (Casanova et al., 2002). A maximum spacing of 500 m is usually applied between VMS on Qatar expressways, which is following the spacing of 500 m between traffic detectors installed along the road (Qatar Ministry of Transport and Communication (MOTC), 2015a).

The first part of the literature review concludes that warning messages for low visibility events should be activated timely enough (i.e., still in the clear zone before transitioning towards the low visibility zone but not too far away from the severe low visibility area). To counteract the misalignment between the weather hazard warning location and the expected impaired visibility (Sándor, 2016; MacCarley et al., 2006), shorter VMS activation distances before the low-visibility events should be tested, which still comply with VMS placements (i.e., 500 m) and the absolute minimum distances between the VMS and changing traffic conditions (i.e., 300 m) (Federal Highway Administration, 2000; Margison, 2008). Moreover, the effect of a VMS sandstorm warning on driving behavior should be analyzed for different impact zones (i.e., clear zone, transition zone, and fog zone) as recommended by the literature (Chang et al., 2019; Wu et al., 2018; Zhao et al., 2019). This includes measurements of mean speeds and deceleration as well as speed variations and the average speed reduction within the low visibility zone.

1.3. Message design for weather-related warnings

A VMS can display text messages and pictograms to warn drivers of incidents ahead (Arbaiza & Lucas-Alba, 2012). The use of graphics and symbols on VMS has been promoted since these representations can be very effective in transmitting information to drivers (Arbaiza & Lucas-Alba, 2012; Ullman, Trout, & Dudek, 2009). Pictograms can be viewed from a greater distance as compared to text messages especially under adverse visual conditions (Ells & Dewar, 1979). Also, especially for non-native speakers, ease of message understanding might substantially be improved by graphics and symbols in case they do not (sufficiently) master the official language used for the composition of text messages. However, previous research pointed out that comprehension of weather-related pictograms is generally very poor (Charlton, 2006). For pictographic messages that specifically address weather conditions, supplementary text messages could optimize the understandability of those messages (Charlton, 2006).

This brings us to another message-related feature that has been shown to have an impact on warning effectiveness, i.e., the linguistic properties of textual messages. Bartlomiejcyk (2013) found that two-line signs (either written monolingual or bilingual) were read without affecting participants' driving behavior, which implies no distraction effects. Different from that, reading four-line messages resulted in unsafe reductions in speed and shorter headway distances (Bartlomiejcyk, 2013) as well as long viewing times for both, bilingual and monolingual drivers, similarly (Jamson et al., 2005). Therefore, irrespective of whether warning messages are mono- or bilingual, in terms of volume and dosage, they should preferably not exceed two text lines (Bartlomiejcyk, 2013). Moreover, the impact of meaningfulness-related criteria (e.g., message specificity, concreteness, the strength of message-behavior associations, etc.) (Ng & Chan, 2007) and framing-related properties (i.e. negative loss-framed messages with high graphic content, and perceived severity that increase persuasion to adjust behavior) (e.g. Horan, 2015) have to be taken into account to improve the effectiveness of a warning. There is tentative evidence indicating that drivers are more inclined to adjust their driving behavior when warnings attract drivers' attention to the negative consequences of an incident instead of a general message (Tay & De Barros, 2010). The drivers' responses to different color and brightness configurations on a VMS as well as the application of flashing beacons to warn drivers of different visibility conditions including daylight as well as night and fog conditions were investigated by Williams et al. (2015). They found that the use of white and amber-on-a black panel improved the detection and legibility distances, whereas the red-on-black color configuration made the sign seem more urgent. Sándor (2016) measured the effect of different weather-related warning messages on motorway traffic in Hungary. He confirmed that a VMS displaying a non-specific hazard warning pictogram in a red triangle with a bilingual description of the hazard was as effective as using specific weather-related pictograms and, therefore, found to be suitable in the context of weather-related warning messages on motorways. Simlinger, Egger, & Galinski, (2008) summarized research regarding the evaluation of warning design elements for VMS displays and found that a simple red triangle is more effective than flashing lights. However, a driving simulator study (Schwarz & Fastenmeier, 2017) pointed out that warnings containing specific information about a hazard (e.g. its position, motion direction, and type) help drivers to better comprehend the relevance of the warning message in situations where the danger itself might still be hidden (i.e. not visible in the imminent traffic environment).

1.4. Warning animation vs. red triangle

Current guidelines generally do not support the use of animated or scrolling text messages (Arbaiza & Lucas-Alba, 2012). However, limited attention has been paid to other design elements on a VMS, such as animated movements and transformations of the pictogram that is an essential part of the warning. Schwarz and Fastenmeier (2018) pointed out that the temporal variation of signs can influence drivers' perception of the corresponding warning. For instance, a temporal visual alteration can increase the perceived urgency of the warning (Baldwin & Lewis, 2014), which can result in higher caution and compliance behavior (Duarte et al., 2014).

Attention allocations and recall of information also seem to depend on the road type. Research has found that in rural areas and on monotonous expressways, drivers remember fewer road signs (Topolšek, Areh, & Cvahte, 2016). Martens & Fox (2007) conducted a driving simulator study and suggested that once drivers are familiar with the roadway, they are less attentive to road signs in the driving environment, which increases the likelihood of overlooking any significant change in road signage and warnings. Chattington et al. (2009) investigated the effect of video and static advertisement on driving behavior and eye fixation in a driving simulator study and found that, in particular, video advertisement attracted attention and increased the glance duration more as compared to a similar static advertisement (Chattington et al., 2009). Computer and online studies from Qatar (Reinolsmann et al., 2020) and Japan (Shiomi et al., 2013) have investigated the impact of information elements on Graphical Route Information Panels (GRIP) to facilitate drivers' comprehension of expressway travel information. The study from Qatar highlighted that a crash warning pictogram and the dynamic update of a green colored bypass was beneficial for driver's response selection. The study from Japan found that pictograms and moving symbols were improving drivers' correct understanding of displayed event information. The authors recommend the use of pictograms and moving symbols to improve drivers' comprehension of weather events such as fog (Shiomi et al., 2013). A VMS guidelines report developed by the Trans-European Road Network (TERN) (Simlinger et al., 2008) highlighted the results of a VMS comprehension study that investigated the impact symbols/pictograms with animated content or with and without a superimposed triangle sign. It was shown that the animated content heightens alertness and facilitates the correct comprehension of rare symbols and pictograms, for instance wrong way driving (e.g. animated oncoming passenger car) and switch off engine if congestion persists (Simlinger et al., 2008). Research on sequences of animated elements was recommended by the state-of-the-art report and should be considered for implementation in cases when significant improvement over non-animated versions of a displayed graphic on a VMS can be achieved (Simlinger et al., 2008). The literature concerning the improvement of comprehension of weather-related warnings remains scarce, even though VMS can display animated graphics or pictograms for different warning purposes. This stands in contrast to the research on the application of design principles for warning messages in the domain of in-vehicle advanced driver assistance technology, which has confirmed that design principles like warning interactivity, dynamic modification and personalization are potentially useful approaches to enhance warning effectiveness (Schwarz & Fastenmeier, 2018).

The literature review suggests that graphical representations of the hazard and specific cues, such as motion direction, can improve the understanding of a graphical warning. Animated elements have shown to attract attention, particularly on monotonous rural expressways, and do occasionally improve drivers’ correct comprehension of rare symbols and situations (Simlinger et al., 2008). But also, red triangles are mostly understood as urgent warnings (Simlinger et al., 2008). A specific weather warning has to be transmitted effectively through the VMS display, considering the diversity of drivers and the diverse share of vehicles with varying technological equipment traveling on the rural expressway in desert regions. However, a particular pictogram of a sandstorm does not exist, and the comprehension of weather-related pictograms on VMS is generally poor (Charlton, 2006). Therefore, the application of animated sand movements towards the drivers' direction will be tested on a VMS display and compared with a default red triangle warning to investigate any differences in driving behavior in the clear, transition, and sandstorm zone.

2. Objective

In this study, we aim to examine the effectiveness of an animated graphic mimicking a sandstorm by showing the movement of sand, resulting in loss of visibility for drivers in a rural expressway setting. The objective is to investigate the effect of a sandstorm animation on driving behavior and to compare it with a general hazard pictogram that does not explicitly communicate the risk of vision impairment. Furthermore, the minimum activation distance between the VMS and the dust cloud was varied between 300 m and 500 m to account for the dynamic location of a sandstorm. The research questions are formulated as follows:

a) To what extent does the distance between the VMS and the low visibility zone affect drivers’ speeds and deceleration behavior in the clear, transition, and low visibility zone?
b) Do the sandstorm animation and the warning pictogram with text differ in effectiveness to influence drivers’ speed reduction within the low visibility zone as compared to no warning?
c) How do drivers evaluate the meaning and implications of both warning strategies?

3. Methodology

3.1. Driving Simulator

The driving simulator allows for safe and controlled observations of driving behavior in replicated weather scenarios. It enables us to proactively investigate a warning message design (i.e., an animated sandstorm warning) that is not yet implemented in real-life. Such a proactive approach is considered to be cost-effective (e.g., Bella, 2010). In this study, we use the driving simulator of the Qatar Transportation and Traffic Safety Center (QTTSC) (see Figure 1).

Figure 1: Driving simulator at QTTSC (Qatar University)

This simulator consists of a fixed-base driving unit (Range Rover Evoque) with a realistic cockpit that provides a force-feedback steering wheel with indicators and a speedometer as well as the gas and breaking pedals with an automatic transmission gearbox. Three large screens are attached to the simulator, which enables a 135 degree of the horizontal field of view with a resolution of 5760 x 1080 pixels. The frame refresh rate accounts for 60 HZ. The simulator is running on STISIM Drive® 3 and is interfaced with CalPot32 for excellent images and sound. Several driving parameters can be logged, such as longitudinal velocity (m/s), acceleration (m/s^2), breaking, etc. The driving simulator present at QTTSC has previously been validated in a study that compared on-road vehicle speeds obtained from an instrumented vehicle with drivers speed choices in the driving simulator (Hussain et al., 2019).

3.2. Warning message designs

Two warning message designs were tested on a gantry-mounted VMS panel. The first design was a sandstorm animation with dense sand moving towards a white SUV, which is the most common vehicle type in Qatar. This animation was accompanied at the right-hand side by the word 'sandstorm' in both Arabic (upper line) and English (lower line) (see Figure 2a). The second panel design showed a generic hazard sign W429 (Qatar Ministry of Transport and Communication (MOTC), 2015c), also accompanied at the right-hand side by the word 'sandstorm' in both Arabic (upper line) and English (lower line) (see Figure 2b).

a) Animation displaying moving sand

b) General hazard warning pictogram

Figure 2: The tested animated warning sign and general hazard pictogram sign

3.3. Scenario design

As for the test scenarios, we replicated sections of Doha Expressway that are located in the rural areas outside the Doha City in the State of Qatar. For this purpose, the Qatar Highway Design Manual (MOTC, 2015b) was reviewed, and video footage of the rural expressway was recorded during clear weather conditions as well as on days with occurring dust haze. A screenshot of the animated sandstorm warning as displayed in the clear zone of the simulation drive is shown in Figure 3a and a screenshot of the low visibility sandstorm zone is presented in Figure 3b. A low to moderate traffic volume, which is the common traffic flow condition in the rural sections of the expressway, was simulated to replicate the situation where unsafe behavior may lead to severe crashes. Besides, it was necessary to limit the impact of surrounding traffic to isolate the impact of the warning design on driving behavior. The eight-lane expressway was separated by a sandy 10 m center median.

a) Simulation view of animated sandstorm warning

b) Simulation view sandstorm affected zone

Figure 3: Simulation view in a) clear zone and b) low visibility zone

The lane width corresponds to 3.65 m with a shoulder width of 3 m. A speed limit of 100 km/h was set for the replicated rural expressway to investigate the effect of the VMS designs in the context of a smart expressway network that can activate variable speed limits. In total, we developed three test conditions, i.e., one control condition (without warning), and two test conditions both including VMS warning messages but different in terms of message-event distance. Two separate simulator drives were developed as shown in Figure 4, with a length of 16.7 km and 18 km, respectively. This provided us with the opportunity to give the participants a break between two drives to counteract fatigue while also not overloading one test drive with sandstorm events.

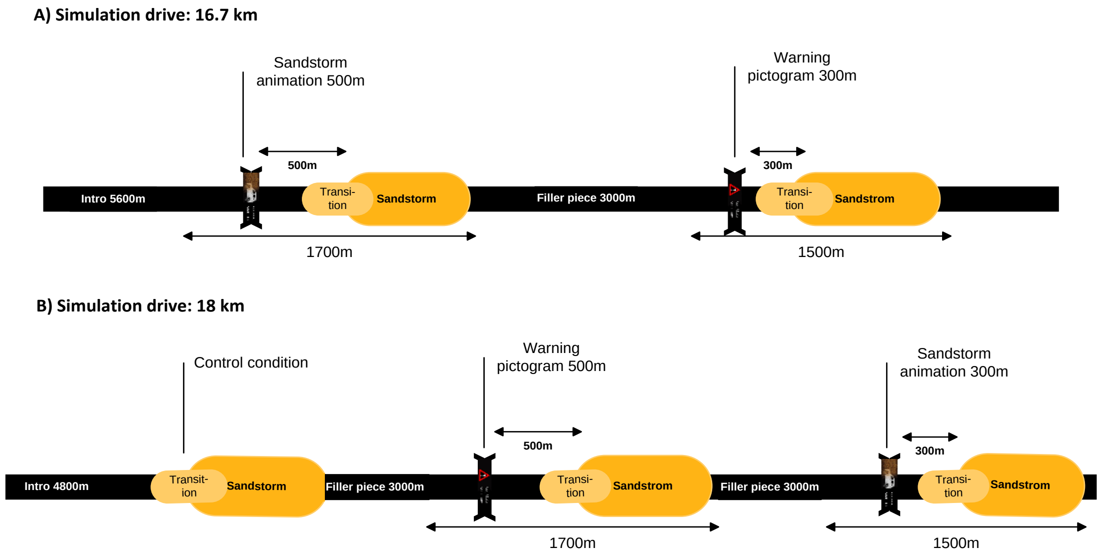


Figure 4: Two test drives (A & B) with developed simulation scenarios

The five scenarios examined (i.e., one control condition and two warning conditions tested at two distances to the sandstorm location) were counterbalanced within the two test drives to prevent learning effects. The order of the two drives was randomized for all participants, and filler pieces were introduced to create an attractive and realistic driving experience.

In the first test condition, the two warning messages previously described were at 100 m away from the so-called 'transition zone', where over a length of 200 m the visibility gradually decreased until the beginning of low visibility. In other words, the total distance between the warning messages and the actual sandstorm was 300 m. The low visibility zone itself was 500 m long with very short visibility levels of 40 m to replicate severe sandstorm conditions as described by Cao et al (2018) and the very low visibility levels as described by Broughton, Switzer & Scott (2007) and Brooks et al. (2011). In the second test condition, the two warning messages were at 300 m away from the dust transition zone. This dust transition zone again covered a distance of 200 m before visibility became very low. In other words, the total distance between the warning messages and the actual sandstorm was 500 m. As the first test condition, the sandstorm zone itself was 500 m long with a very short visibility distance of 40 m. For the control condition, the dust transition zone and low visibility zones were equally long as in the test conditions (i.e., dust transition zone = 200 m; low visibility zone = 500 m). The only difference with the test conditions was that the control condition did not include a sandstorm warning.

3.4. Procedure

This study was reviewed and approved by the ethical committee of Qatar University. For the driving simulation, we invited participants who had a valid Qatari driving license. Participants were recruited through posters and brochures that were handed out at various public events in Qatar, as well as social media. We also sent out recruitment emails with a link to the registration website through the email database of QTTSC at Qatar University.

Participants were invited to the driving simulator lab and had to sign an informed consent form. All participants were informed about their rights and the possible occurrence of simulation sickness. First, a pre-questionnaire was administered to collect socio-demographic data and car usage habits. Afterward, participants were introduced to the simulator mock-up and were invited to do a test drive to get acquainted with the driving controls and to practice driving maneuvers in a simulated environment. Participants received the instruction to drive as they would normally do on the expressway. The participants were not aware of the purpose of the study nor of the content of the test drives. After completion of the two scenarios of the main experiment, participants were asked to fill in a computer-based post-test questionnaire to evaluate the sandstorm warning designs. In particular, they had to use a 5-point Likert scale to rate the design features of the presented VMS warnings. The following attributes, as proposed by Ng & Chan (2007), were rated: familiarity, concreteness, simplicity/complexity, meaningfulness, and semantic closeness (i.e., strength of association).

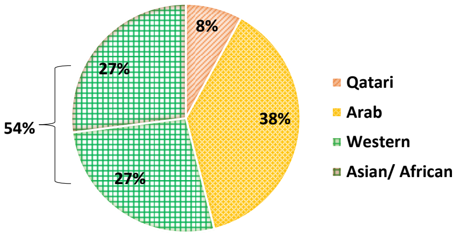
3.5. Data collection and analysis

Mean speed in kilometers per hour (km/h) is an important indicator for safe driving since higher speeds are associated with an increased crash risk and severity (Elvik et al., 2009). The standard deviation of speed (SD speed) is also considered to be an important parameter since speed variances among drivers are associated with disruptive traffic flows and higher crash rates (MacCarley et al., 2006; Marchesini & Weijermars, 2010). Longitudinal acceleration/deceleration (AD) is used to identify aggressive deceleration or braking events (Ahmed, 2016). Data were extracted from 500 m before the VMS up to the end of the low visibility sandstorm event and outro transition. Zonal based driving parameters were investigated for the clear, transition, and low visibility sections. Since all participants were exposed to all driving conditions, a within-subject repeated measures design was chosen. The effects of the conditions (no warning, animation, generic pictogram) and the tested distances (500 m, 300 m) to the low visibility zone were investigated using a multivariate analysis of variance (MANOVA). The driving parameters 'mean speed', 'SD speed', and 'AD' were further investigated through an analysis of variance (ANOVA) and Bonferroni corrected pairwise comparisons. A significance level of 0.05 was selected for all analyses to evaluate the significance of the results, and the Greenhouse-Geisser correction epsilon was used to adjust for lack of sphericity (Field, 2013).

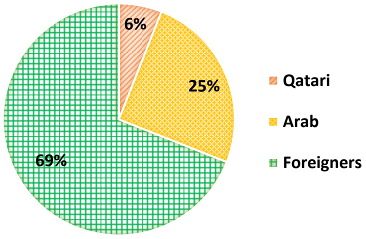
4. Results

4.1. Participants

For this study, seventy-two participants were recruited, of which four did not finish all test drives due to simulation sickness. Additionally, five outliers were found when analyzing the mean speed box plots for every condition. A driver was marked as an outlier and removed from the study if his/her mean speed was larger than three times the SDs of the sample in at least one test situation (Field, 2013). Thus in total, sixty-three participants were included in the final analysis. The descriptive results revealed that 29 nationalities participated in the study. Figure5a shows that 38% of the drivers are coming from Arabic countries and 8% of the sample were Qatari nationals. Fifty-four percent of drivers had other origins, with 27% coming from Western countries and 27% of the drivers having an Asian or African background. Data from the Ministry of Interior (see Figure5b) confirmed that foreigners represent the highest share of driving license holders in the State of Qatar (Qatar Planning and Statistics Authority, 2018). In total, 59% of participants were male, and 41% were female. The average age was 31 years, with an overall age range from 18 to 57 years. On average, drivers owned their first driving license for 10 years. Thirty percent of drivers owned a Qatar driving license for less than 2 years, while 70% of drivers had their license already for more



a) Origin of 63 drivers in sample



b) Registered active driving licenses (245,384)

Figure 5: drivers' origin (sample) as compared to driving license holders in Qatar in 2018

than 2 years. Most drivers indicated to be fully employed (68%). Twenty-nine percent of drivers were occupied as students, and 3% indicated to be under the sponsorship of a family member. Almost 50 % of drivers drove about 10,000-20,000 km per year, whereas 25.5% of the drivers spent more than 20,000 km per year on the road. Most participants drive a car with an automatic transmission (89%).

4.2. Effect of VMS warning distance on mean driving speed

A repeated measures within-subjects MANOVA was conducted to investigate the main and interaction effects for condition (control vs. animation vs. warning pictogram) and distance (300 m vs. 500 m before the low visibility) (see Table 1). A significant interaction effect was found between the conditions and the 50 m measurement zones ($F_{(11;685)}$=4.25; p<0.001, ηp^2=0.064).

Moreover, two separate repeated measures analyses of variances (ANOVA) were conducted to investigate the impact of the conditions on longitudinal driving parameters over the different zones

Table 1: MANOVA: main and interaction effects between conditions and zones

MANOVA				
Effect	**F**	**Df**	**p- value**	**ηp²**
Condition	9.460	3; 176	<0.001**	0.132
Zones	206.948	2; 127	<0.001**	0.769
Condition x Zones	4.248	11;685	<0.001**	0.064

*significant at α< 0.05 ** significant at α< 0.01

if the gantry was located 300 m or 500 m from the sandstorm.
Table 2 displays the impact on driving parameters if the VMS would be activated 500 m before the sandstorm. Mean speeds and mean AD were also significantly affected over the 500 m distance. However, this time no variations in driving speeds were found.

Table 2: ANOVA: driving parameters for distance 500 m

Within-Subjects Effects for Condition x Zones (Greenhouse-Geisser)				
Effect	**F**	**Df**	**p-value**	**ηp²**
Mean speed	4.723	7; 434	<0.001**	0.071
SD speed	1.379	11; 672	0.179	0.022
Mean acceleration	1.953	13; 824	0.021*	0.031

*significant at α< 0.01 ** significant at α< 0.05

Table 3 shows the results for a sandstorm warning 300 m in advance. Mean speeds and mean acceleration/deceleration (AD) were significantly affected by the conditions and zones. Also, variations in driving speeds (SD speed) were significant, which represent heterogeneous speeds among drivers.

Table 3: ANOVA: driving parameters for distance 300m

Within-Subjects Effects for Condition x Zones (Greenhouse-Geisser)				
Effect	**F**	**Df**	**p- value**	**ηρ²**
Mean speed	5.968	6; 379	<0.001**	0.088
SD speed	3.454	13; 764	<0.001**	0.053
Mean acceleration	3.230	13; 832	<0.001**	0.050

*significant at α< 0.01 ** significant at α< 0.05

An overlay of drivers' mean speeds in the clear, transition, and low visibility zone was done to compare all test conditions (e.g. 300 m or 500 m distances for sandstorm animation and warning pictogram) with the control condition. Figure 6 shows the mean speed trajectory of the drivers in all conditions using different line styles. The VMS gantry location for the 500 m warning distance would be located at 500 m on the x-axis, whereas the VMS location for the 300 m warning distance would be at 700 m on the x-axis. It is aimed to investigate for all conditions the driving speeds in the last 100 m of the clear zone, the last 100 m of the transition zone and the first 300 m into the low visibility zone.

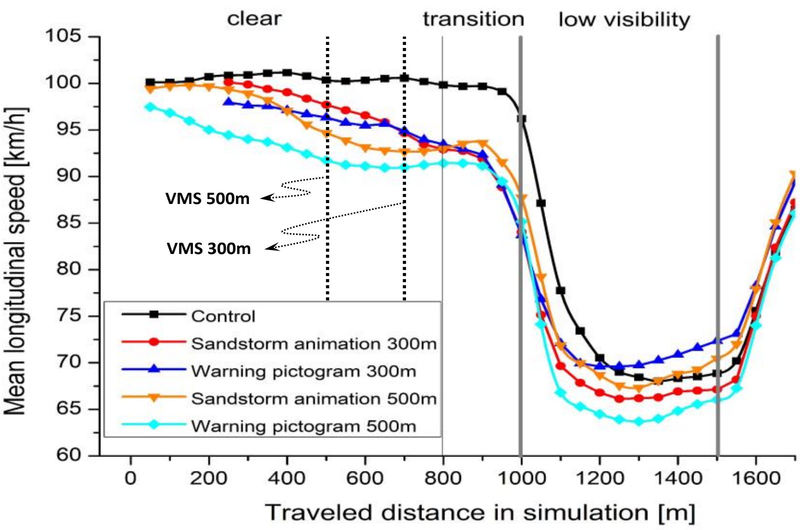


Figure 6: Mean driving speeds across all conditions for clear, transition, and low visibility zone

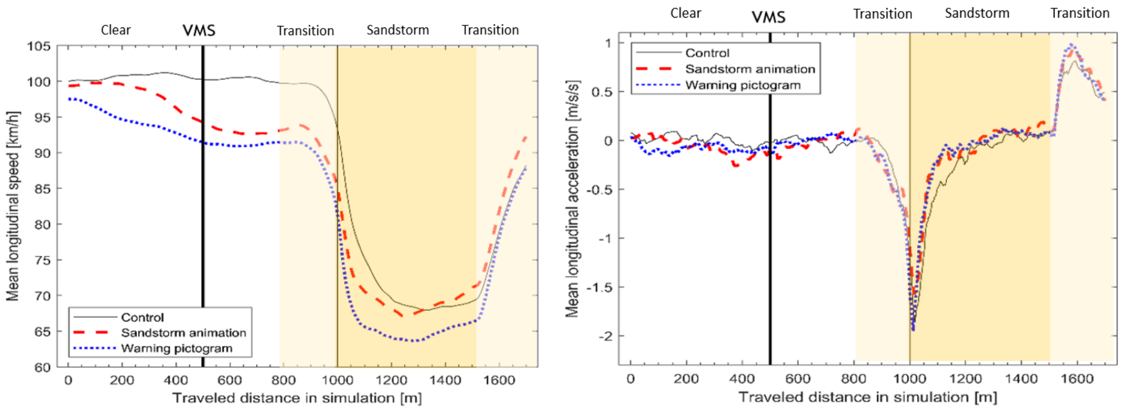
Clear zone: A posthoc ANOVA with Bonferroni corrections for pairwise comparisons was conducted to compare the driving speeds for all conditions in the clear zone at 700-750 m (see Figure 6). The results revealed that the 'sandstorm animation 500 m' (-7.48 km/h, $F_{(3,202)}=7.01$, $p<0.001$), the 'warning pictogram 500 m' (-8.95 km/h, $F_{(3,202)}=7.01$, $p<0.001$) and 'warning pictogram 300 m' (-6.24 km/h, $F_{(3,202)}=7.01$, $p=0.021$) were significantly different from the control condition at 750 m. Only, the 'sandstorm animation 300 m' was not yet significantly different from the control condition (-6.72 km/h, $F_{(3,202)}=7.01$, $p=0.068$).

Transition zone: After 100 m into the transition zone (i.e., 900-950 m), all conditions were significantly different from the control condition with 10 km/h lower mean speeds for the 'sandstorm animation 300 m' ($p=0.002$) and 'warning pictogram 300 m' ($p=0.001$), as well as 9.6 km/h lower mean speeds for the 'warning pictogram 500 m' (p=0.001) and 7.6 km/h lower mean speeds for the 'sandstorm animation 500 m' (p=0.005).

Sandstorm zone: Only within the low visibility zone, differences in driving speeds for the warning pictogram at different distances become evident. Whereas the sandstorm animation activated either at a distance of 500 m or 300 m resulted in similar driving speeds within the low visibility zone, did the warning pictogram condition activated at 500 m and 300 m display great differences. Bonferroni corrected pairwise comparisons showed that at 1300 m traveled distance (300 m into the low visibility zone) the 'pictogram warning 500 m' had resulted in significantly lower mean speeds as compared to the 'pictogram warning 300 m' (6.25 km/h, $F_{(3,211)}$ =4.47, p=0.001, ηp^2=0.067). Therefore, further analyses were required to investigate the zonal impact of the warning conditions on driving behavior for the two tested distances to the low visibility area.

4.3. Distance to Sandstorm

In Figure 7a-b the mean speed and mean acceleration for the conditions activated at a distance of 500 m to the sandstorm zone were plotted. The black vertical line at 500 m shows the location of the warning VMS, whereas the low visibility zone starts from the grey vertical line at 1000 m. In this scenario, the 200 m transition zone starts 300 m after the VMS location. The descriptive values are summarized in Table 4.



a) b)

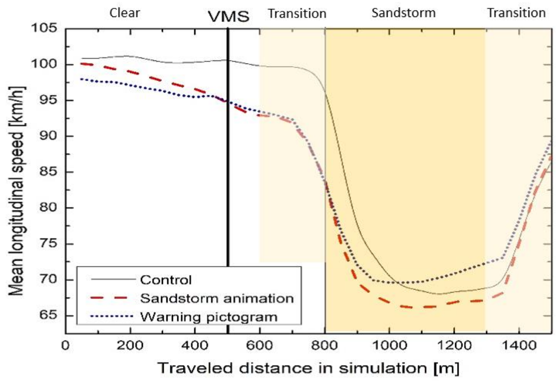
Figure 7: mean speeds and mean acceleration over 500 m warning distance

Table 4: Descriptive statistics: mean speeds and mean acceleration for conditions 500 m distance

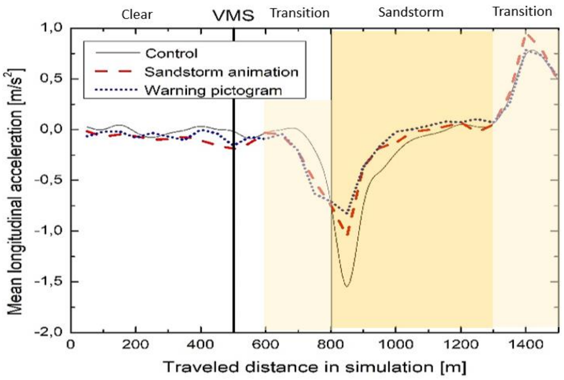
Scenario	Measures		Clear zone before VMS	500 m distance: Clear zone after VMS (300 m)	500 m distance: Transition zone (200 m)[1]	Sandstorm zone (500 m)	Transition zone (200 m)[2]
Control (no VMS)	a) Mean speed	Mean	100.904		98.676	71.726	78.542
		SD	12.912		12.801	14.998	13.55
	b) Mean acceleration	Mean	-0.013		-0.23	-0.266	0.565
		SD	0.327		0.448	0.523	0.516
Sandstorm animation	a) Mean speed	Mean	97.003	93.043	91.604	68.608	81.342
		SD	15.449	13.846	14.826	15.017	13.979
	b) Mean acceleration	Mean	-0.125	-0.028	-0.263	-0.179	0.641
		SD	0.399	0.346	0.593	0.582	0.504
Warning pictogram	a) Mean Speed	Mean	92.426	91.162	89.3	64.963	77.144
		SD	14.674	13.57	15.156	13.708	11.877
	b) Mean acceleration	Mean	-0.092	-0.001	-0.318	-0.177	0.627
		SD	0.378	0.405	0.504	0.532	0.516

Note: [1] Transition zone before the sandstorm reduced visibility, [2] Transition zone after the sandstorm reduced visibility

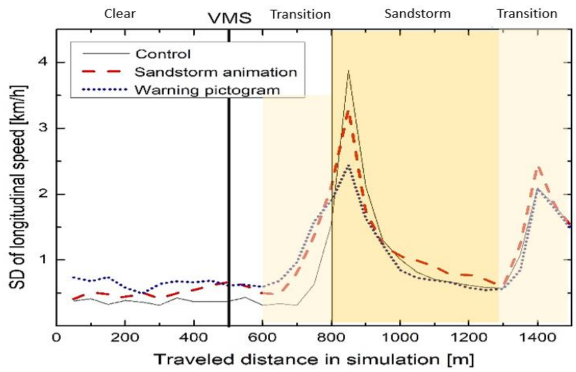
The significant driving parameters mean speed, mean acceleration, and SD speed for the conditions at 300 m distance are displayed in Figure 8a-c. The bold black line at 500 m indicates the location of the VMS (only available in the warning conditions) and the vertical grey line at 800 m represents the beginning of the actual sandstorm. The averaged descriptive values per clear, intro transition zone (200 m), low visibility zone (500 m), and outro transition zone are summarized in Table 5.



a)



b)



c)

Figure 8: mean speed, mean acceleration, SD speed over 300 m warning distance

Table 5: Descriptive statistics: mean speeds, mean acceleration and SD speeds for conditions 300m distance

Scenario	**Measures**			**Clear zone before VMS**	**300 m distance**		**Sandstorm zone (500 m)**	**Transition zone (200 m)[2]**
					Clear zone after VMS (100 m)	**Transition zone (200 m)[1]**		
Control (no VMS)	a)	Mean speed	Mean	100.357		98.676	72.00	78.542
			SD	12.748		12.801	14.998	13.55
	b)	Mean acceleration	Mean	-0.017		-0.361	-0.004	0.633
			SD	0.326		0.448	0.523	0.457
	c)	SD speed	Mean	0.399		1.541	0.933	1.626
			SD	0.525		0.82	1.108	1.096
Sandstorm animation	a)	Mean speed	Mean	96.65	93.189	89.384	67.911	78.212
			SD	15.889	15.23	16.006	15.66	13.73
	b)	Mean acceleration	Mean	-0.117	-0.082	-0.435	-0.163	0.64
			SD	0.482	0.353	0.678	0.535	0.495
	c)	SD speed	Mean	0.557	0.554	1.192	1.207	1.755
			SD	0.727	0.605	1.593	1.186	1.076
Warning pictogram	a)	Mean speed	Mean	95.799	93.704	89.53	71.286	81.351
			SD	15.970	15.782	16.04	15.682	14.628
	b)	Mean acceleration	Mean	-0.069	-0.083	-0.32	-0.066	0.571
			SD	0.466	0.412	0.76	0.456	0.493
	c)	SD speed	Mean	0.657	0.626	1.486	0.831	1.541
			SD	0.71	0.629	1.634	0.942	1.014

Note: [1] Transition zone before the sandstorm reduced visibility, [2] Transition zone after the sandstorm reduced visibility

Separate posthoc pairwise comparisons with Bonferroni corrections were conducted for the 50 m zones within the sections of interest (e.g. clear zone, intro-transition zone, sandstorm zone) as shown in Figure 7 and Figure 8.

4.3.1. Driving behavior in the clear zone

For the 500 m VMS distance, a systematic earlier decrease in mean speeds (Figure 7a) was measured already from 400 m before for the pictogram warning as compared to the control condition (-4.28 km/h, $F_{(2,122)}$=4.67, p=0.03) and the sandstorm animation (-3.81 km/h, $F_{(2,122)}$=4.67, p=0.03). At 100 m before the VMS significant lower mean speeds of 5.19 km/h were also found for the sandstorm animation ($F_{(2;110)}$=10.04, p=0.032) and even lower mean speeds of 8.36 km/h for the pictogram warning ($F_{(2;110)}$=10.04, p=0.001) as compared to the control condition.

For the 300 m VMS distance (Figure 8a), a significant difference in mean speeds was found between the pictogram warning and no warning after 350 m traveled distance (i.e., 150 m before the VMS location). Drivers responded to the pictogram warning by reducing their mean speed by 4.86 km/h as compared to the control condition ($F_{(2;104)}$=3.38, p=0.039). Also, the mean speeds for the sandstorm animation differed significantly from the control condition after 450 m traveled distance. A speed reduction of 5.89 km/h ($F_{(2;108)}$=5.87, p=0.037) was found for the 'sandstorm animation 300 m' and a speed reduction of 5.67 km/h was observed for the 'pictogram warning 300 m' ($F_{(2;108)}$=5.87, p=0.009) as compared to the control condition.

4.3.2. Driving behavior in transition zone

When activated a the 500 m distance to the sandstorm, the first 50 m within the transition zone (i.e., 800-850 m) were characterized by a significant difference between the control condition and both warning conditions with 6.16 km/h lower mean speeds for the 'sandstorm animation 500 m' ($F_{(2;109)}$=10.24, p=0.004) and 8.25 km/h lower mean speeds for the 'pictogram warning 500m' ($F_{(2;109)}$=10.24, p=0.001). This effective reduction continued throughout the transition zone until the low visibility section was reached.

For the 'sandstorm animation 300 m', significantly lower mean speeds of 6.94 km/h ($F_{(2;101)}$=6.98, p=0.019) were measured at the beginning of the transition zone (i.e., 600-650 m) as compared to the control condition. Also, 6.72 km/h lower mean speeds were obtained for the 'pictogram warning 300 m' ($F_{(2;101)}$ =6.98, p=0.011) as compared to the control condition. At the end of the transition zone (i.e., 750-800 m), the sandstorm animation 300 m resulted in further speed reductions of 12.17 km/h ($F_{(2;112)}$=18.37, p<0.001) and the 'pictogram warning 300 m' reduced mean speeds by 12.51 km/h ($F_{(2;112)}$=18.37, p<0.001) more than the control condition. No differences were found between the two warning designs. The sandstorm animation (-0.49 m/s^2, $F_{(2;113)}$=6.02, p=0.006) as well as the pictogram warning (-0.65 m/s^2, $F_{(2;113)}$=6.021, p<.001) resulted in significant decelerations already 50 m earlier than in the control condition (Figure 8b).

4.3.3. Driving behavior in low visibility zone

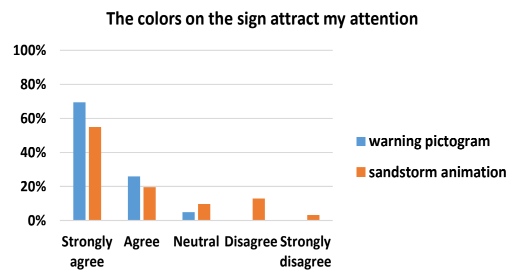
When entering the low visibility zone at 1000 m traveled distance, significantly lower mean speeds of 7.88 km/h for the 'sandstorm animation 500 m' ($F_{(2;101)}$=15.33, p=0.003) and 13.00 km/h for the 'pictogram warning 500 m' ($F_{(2;101)}$=15.33, p<.001) were found as compared to the control condition (Figure 7a). Also, a significant difference between the two warning designs was found after 50 m in the sandstorm. The pictogram warning decreased the average driving speed by 5.13 km/h more as compared to the sandstorm animation ($F_{(2;101)}$=15.33, p=0.026). A significant mean speed difference of 4.66 km/h remained between the two warning designs ($F_{(2;112)}$=12.29, p=0.003) during the entire length of the low visibility zone, which demonstrates that the pictogram warning had a more distinct and longer effect on speed reduction within the low visibility sandstorm area as compared to the sandstorm animation. Overall, a speed reduction of 5% was achieved for the sandstorm animation and a speed reduction of 10% was achieved for the pictogram warning. When looking at the deceleration values of both warning designs (see Figure 7b) it was shown that they were very similar and deviated significantly from the control condition after 100 m into the sandstorm (e.g., animation warning ($F_{(2;97)}$ =6.16, p=0.037) and the pictogram warning ($F_{(2;97)}$=6.16, p=0.022)). This indicates that the drivers were able to stabilize their deceleration earlier as in the control condition.

Regarding the 300 m warning distance, a pairwise comparisons for driving speeds revealed that the 'sandstorm animation 300 m' reduced the mean speeds at the beginning of the low visibility zone (800-850 m traveled distance) significantly by 11.98 km/h ($F_{(2;116)}$=16.35, p<0.001) and the pictogram warning did also achieve significant lower mean speeds of 10.31 km/h as compared to the control condition ($F_{(2;116)}$=16.35, p<0.001). The sandstorm animation performed very well until 150 m into the low visibility sandstorm area as can be seen in Figure 8a with significantly lower mean speeds of 5.58 km/h as compared to no warning ($F_{(2;114)}$=4.98, p=0.013). After 250 m driving into the low visibility area, a first significant difference was found between the two warning conditions with -3.54 km/h lower mean driving speeds in the sandstorm animation as compared to the pictogram warning ($F_{(2;121)}$=5.35, p=0.042). This difference continued until the end of the sandstorm area, where -5.21 km/h lower driving speeds were found for the sandstorm animation as compared to the pictogram warning ($F_{(2;116)}$=5.16, p=0.004). An overall speed reduction of 6% was achieved for the sandstorm animation, whereas a speed reduction of only 1% was gained for the pictogram warning throughout the sandstorm zone. The graphs in Figure 8b indicate that the strongest deceleration peak took place after the start of the low visibility zone (i.e., 800-850 m traveled distance) in the control condition, followed by smoother and less steep decelerations for the 'sandstorm animation 300 m' and the 'warning pictogram 300 m'. The pairwise comparisons revealed that both warning conditions significantly smoothed the strong deceleration peak that was measured in the control condition. We found -0.50 m/s^2 decreased deceleration in case of the sandstorm animation ($F_{(2;124)}$=10.78, p=0.010) and -0.72 m/s^2 lower decelerations if the pictogram warning was activated 300 m before the event ($F_{(2;124)}$ =10.78, p<0.001), indicating safer breaking behavior. The speed variations shown in Figure 8c were higher for the control condition at their peaks and were significantly reduced only by the 'pictogram warning 300 m' by 1.44 ($F_{(2;121)}$=5.99, p<0.001), which indicates that drivers adjusted their speeds more homogeneously.

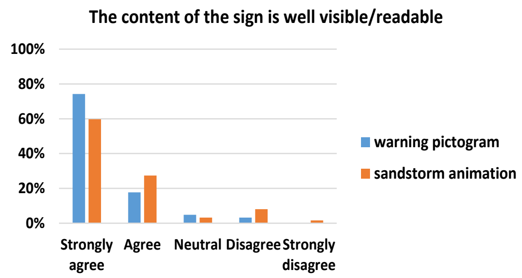
4.4. Comprehension and design preferences

Drivers' comprehension of the warning design, the conspicuity of features, and the sign-content compatibility are important aspects of safety-related message signs since they can deliver useful insights in message compliance (Bazire & Tijus, 2009; Ben-Bassat & Shinar, 2006). Figure 9 shows the warning design ratings according to the meaningfulness-related criteria (e.g., message specificity, familiarity, the strength of message-behavior associations, etc.) as proposed by Ng & Chan (2007). The results are presented for seven items that were evaluated by the drivers using a 5 point Likert scale after completion of the driving experiment. As can be seen in Figures 9a and 9b, the majority of the participants strongly agreed that the warning pictogram mostly attracted their attention due to the red color used and that the content was well arranged (69.4% and 74.2%, respectively), making the sign easy to read from a distance. The majority of drivers (i.e., 77.4%) indicated that they were very familiar with the general hazard symbol of the warning pictogram, whereas, for the sandstorm animation, no evident agreement was seen among the respondents (see Figure 9c). The heterogeneous distribution of drivers' familiarity with the displayed animation could arise since the car icon and the sand movements are recognizable in a general context, but the combination has not been seen before.

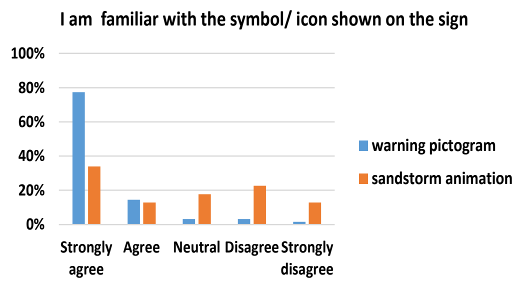
Figures 9d and 9e show that there is no clear agreement among drivers whether the generic pictogram or the sandstorm animation is better in transmitting the meaning of the hazard ahead (92% vs. 87%) and for providing implications for behavior (80% vs. 84%). However, the pictogram was evaluated as not being related to the issue of poor visibility. Instead, the sandstorm animation did score very well since 67.7% of the driver did strongly agree that the animation is clearly referring to the issue of poor visibility ahead and an additional 25.8% of the drivers did agree with this statement (Figure 9f). Neither of the two warning signs was evaluated as complex or difficult to understand (Figure 9g). Drivers' overall preferences (Figure 9h) revealed that 44.4% of all respondents preferred the sandstorm animation, while 39.7% of drivers preferred the pictogram warning to be activated before the sandstorm. On the other hand, 15.9% of the drivers indicated that a warning is not necessary since these drivers would only adjust their speeds if they can confirm the low visibility by their own eyes. These observations are also in line with fog-related studies (e.g., Jeihani & Banerjee, 2019; Wu, Abdel-Aty, Park, & Selby, 2018; Yan et al., 2014; MacCarley et al., 2006), which confirmed that drivers don't adapt their driving speeds if the fog level is not perceived as severe. The participants were also asked to indicate the relevance of the bilingual text message. It was shown that 45.2% of the drivers first looked at the Arabic text to read the warning, while 54.8% looked at the English text to read the warning, which corresponds to the proportion of Qatari/Arab drivers vs. other nationalities in our sample.



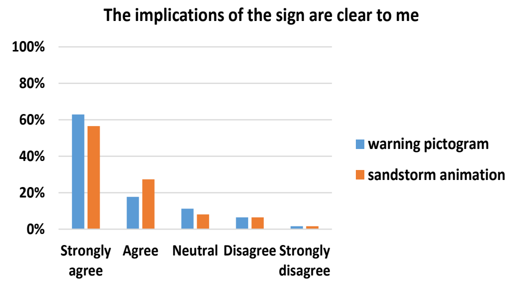
a) Criteria 1: Conspicuity



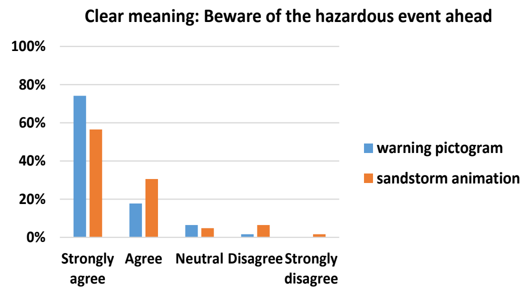
b) Criteria 2: Readability



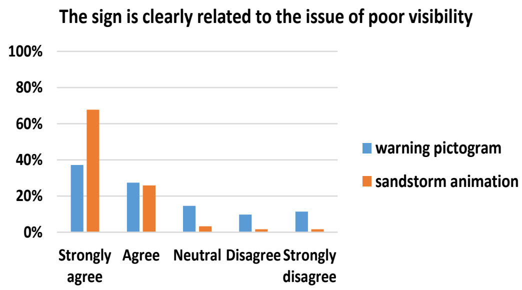
c) Criteria 3: Familiarity



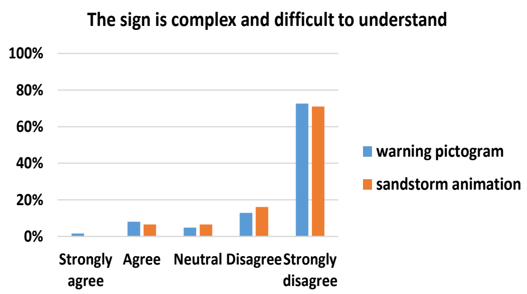
d) Criteria 4: Implications



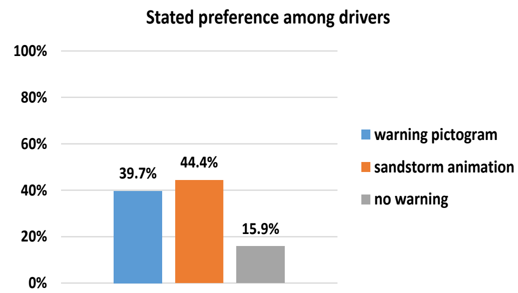
e) Criteria 5: Delivered meaning



f) Criteria 6: Issue-relatedness



g) Criteria 7: Complexity



h) Overall preference

Figure 9: Drivers sign evaluation: 7 meaningfulness-related criteria (Ng & Chan, 2007) and overall preference

Finally, the survey revealed that 22.6% of the drivers indicated that they would reduce their speed immediately after seeing the warning, whereas 16.1% of drivers reported that they would slow down after passing the sign, and 43.5% of drivers indicated that they would slow down when seeing a slight change in weather conditions (i.e., transition zone). Besides, 16.1% of the drivers reported that they would only slow down when the visibility was severely reduced, while only 1.6% of drivers stated that they would not reduce speeds at all.

5. Discussion

Sandstorm conditions degrade visibility, which can have severe consequences for safe driving behavior. Particularly, when entering the sandstorm affected area, the visual contrast decreases, and drivers' vision is severely impaired. Given the heterogeneous driving population in Qatar, it was aimed to implement a VMS warning that can effectively transfer the meaning and consequences of a sandstorm to the drivers and prepare them to reduce their speeds. Since VMSs offer the advantage of displaying animated graphics on the matrix panel, it was decided to compare a sandstorm text message either displayed with a standard hazard pictogram or with an animated graphic of moving sand to investigate drivers' understanding of the hazard situation and the implications for safe driving as compared to no warning. Moreover, we have addressed the dynamic nature of a sandstorm event that can result in shifting sand clouds at particular road sections in the vicinity of a VMS. The VMS gantries on rural expressways are usually installed at larger distances from each other. Warnings can be issued already from far distances. However, since the far alignment from the low visibility zone can decrease the warning effectiveness (MacCarley et al., 2006), it was aimed to investigate the minimum activation distance of available VMS gantries to still be effective.

5.1. Distance to the sandstorm

The study results showed that the impact of the VMS activation at 500 m or 300 m on driving behavior is not significantly different in the crucial sections of the transition zone and the beginning of the low visibility zone. The sandstorm animation and the general hazard pictogram did effectively reduce driving speeds and improved the onset of decelerations for smooth speed reductions before entering the low visibility zone as compared to no warning. Moreover, the warning designs did not differ in their deceleration rate and effectively prepared drivers to conduct an earlier and smoother speed reduction already in the transition zone. The variation in speeds within the low visibility zone were significantly reduced by the pictogram warning from the 300 m distance but not necessarily with the sandstorm animation 300 m, which indicates that the drivers homogeneously stabilized their driving speeds at 71 km/h for the pictogram condition, whereas more speed variations are possible in the sandstorm animation at 300 m distance. Speed variations were generally insignificant for the 500m distance, which is in line with the study of MacCarley et al. (2006), which applied VMS distances of 800m to a low visibility zone. Our study also showed that the average speeds collected 300m after the VMS were reduced by 6.7- 6.9 km/h for both tested warning designs whereas Cooper & Sawyer (2005), reported only an average speed reduction of 2.9 km/h measured after 300 m for several VMS fog warnings. It can be summarized that both distances to the sandstorm showed a strong impact on reducing driver speed and improving drivers' preparedness to enter the low visibility road section. This means that authorities have some flexibility when to activate available VMS panels and they will still have an impact even if the distance between the sandstorm location and the VMS becomes shorter. The benefits of low speed variations at the beginning of the sandstorm zone became evident for the red triangle pictogram warning at the short distance of 300 m, which is in line with the highway guidelines for VMS implementation (Margison, 2008).

5.2. Driving within the sandstorm

Unexpected differences were found within the low visibility zone. The mean driving speeds were generally reduced by 5 - 6 % in the sandstorm animation conditions. In contrast, there were clear differences between the pictogram warning issued at 500 m (resulting in 10% speed reduction) and the pictogram warning displayed at 300 m before the low visibility zone (resulting in an average of 1% speed reduction). This is remarkable since the drivers were not informed of the distance to the actual sandstorm and the actual hazard was not visible at the time looking at the warning display. Within the low visibility, zone drivers behaved similarly for the sandstorm animation in both distance scenarios, whereas for the warning pictogram the drivers' speed reduction percentage varied within the same low visibility zone. Drivers have likely obtained experience while driving under low visibility conditions and appear to have different expectations regarding the actual hazard that is warned for. More specifically, the generic hazard pictogram is aimed to make drivers more cautious about general hazards. In one test drive, drivers adjusted their driving speeds already when the pictogram warning became visible at the far distance and drove at lower driving speeds within the low visibility zone, which is in line with Williams et al. (2015) who suggested that the application or a red-on-black color configuration makes a sign seem more urgent for behavioral adaptations. However, when being exposed to the pictogram warning after previously having experienced another sandstorm warning, the speed adaptations were less pronounced within the low visibility zone. Interestingly, the mean driving speeds appeared to increase within the low visibility zone since the drivers cannot find any other traffic hazards on the expressway except for low visibility. In contrast, drivers' speed adjustment within the low visibility zone remained rather constant for the sandstorm animation over both test drives.

5.3. Design implications for behavior

The drivers' evaluation of the graphical design of both VMS warnings showed that the majority of drivers preferred the implementation of a warning in general. More particularly, the sandstorm animation was perceived to be strongly related to the issue of low visibility, whereas this was not the case for the pictogram warning. Overall, the sandstorm animation was only preferred over the general warning pictogram by an additional 5% of the drivers, which can be attributed to the fact that the warning pictogram is accompanied by the text message 'Sandstorm' to specify the hazard. It is likely that drivers do also concentrate on the text, which was displayed in English and Arabic. On the other hand, the sandstorm animation provides a bilingual text but further specifies the consequences of the sandstorm hazard in terms of low visibility through turbulent sand. Our study found that 67.7% of the driver did strongly agree that the animation is unquestionable referring to the issue of poor visibility with an overall of 93.5% of drivers who correctly agreed on the transferred meaning of 'low visibility ahead'. The high sign recognition ability among international drivers is promising considering that the ISO9186-1: 2007 standards specify that a symbol can be accepted if 67% of the users understand it clearly or if the sign is generally understood by 85% of the users to be standardized in the United States (ANSI Z5353) (Talab & Azari, 2017). However, additional studies are necessary to investigate the drivers' sign comprehension of the animated graphic as a standalone sign without the additional text. Furthermore, future eye-tracking applications would be interesting to capture the drivers' eye glance percentages towards the text message and the pictogram or animated graphic on the VMS. So far, the driving simulator study was able to show that driving speeds decreased homogeneously in the clear zone when passing the activated VMS warning designs.

Furthermore, the unexpectedly different speed reduction percentages between the two test drives with a pictogram warning might be attributable to the drivers' heterogeneous understanding of the hazards that can be encountered in a sandstorm. In this research, the impact of surrounding traffic on driving behavior was kept minimal to investigate drivers' speed choices under free-flow conditions and to avoid the occurrence of lagger behavior (Broughton et al., 2007; Saffarian et al., 2012). However, the repeated encounter of the sandstorm event in the simulation drives is likely to establish an expectation effect that no additional hazards except for low visibility will occur. It is stated in the literature that familiarity and expectations are likely to influence drivers' perception and behavior over repeated driving situations (Martens & Fox, 2007). If initial hazard expectations are not met, likely, drivers would not respond to a warning anymore. Research has found that drivers who become familiar with a site tend to perform similarly in a situation despite a change in traffic signs (Martens & Fox, 2007). The different speed reduction percentages for the warning pictogram are probably the result of drivers who first attempted to drive carefully within the low visibility zone (10% speed reduction), whereas after the experience of a sandstorm and its visibility level, the drives did not expect to encounter any additional traffic hazard on the rural expressway, which resulted in the slight increase in driving speeds at the end of the low visibility zone as compared to the control condition. In the case of a sandstorm animation the speed reduction percentage appeared to be constant over all test drives (5%-6%), which can be attributed to the drivers' understanding that the issue of low visibility due to fine sand particles in turbulent air represents the safety hazard. Considering the high average driving speeds on rural expressways, this relative change in speed can have an important impact on the number and severity of crashes (Elvik, 2013), particularly at the beginning of the low visibility zone.

5.4. Limitations and considerations

A limitation of this study can be the order of conditions in the two counterbalanced test drives. However, the test drives were designed in a way to minimize the learning effect of VMS locations and the occurrence of sandstorms, which was rather unpredictable than it would be in the case of separate condition-specific test drives. Another limitation might be the actual perceived danger of driving in a sandstorm situation, which can deviate from reality despite the high-quality images in the driving simulation and the simulated wind gust. Therefore, it would be interesting to test the sandstorm animation for naturalistic driving conditions and changing visibility levels. Furthermore, the interaction of responses to weather warning signs under varying traffic densities and hazard situations can be included. Consideration must also be given to the heterogeneous and international driving population in this study when generalizing the results to other countries with less diverse driver backgrounds. However, a similar age range as proposed in this study should be pursued to test drivers' perception of variable safety signs to control for aging-related effects such as reduced cognitive functioning and poor (color) vision. Research should further focus on the effectiveness of animated graphical elements in warning messages on VMS as well as for in-vehicle warning systems.

6. Conclusion and Practical Applications

It can be concluded that drivers understood the pictogram and animation warning on the VMS since text was added to both designs stating 'Sandstorm'. Thus, both VMSs have a similar positive impact. However, the sandstorm animation was better understood among drivers to be related to the issue of low visibility being the safety hazard. A general warning pictogram with the text line "sandstorm" can also refer to other possible traffic hazards that can be encountered on the expressway.

Both VMS activation distances of 300 m or 500 m before the low visibility zone are suitable to improve drivers' preparedness to safely adjust their driving behavior and to effectively reduce speeds as compared to the scenario without a warning. Although this paper deals with the specific situation of sandstorm induced low visibility, the results of the display designs and minimum activation distance of the VMS warning can be generalized to other domains, such as fog warning. This study has shown that a warning is still effective in influencing drivers' speed reduction at the end of the transition zone and the beginning of the low visibility zone even if displayed only 300 m before. These insights provide roadway authorities with more flexibility to display a sandstorm warning using prevailing on-road infrastructure or in case the implementation of costly VMS infrastructure has to be spaced over larger distances on the rural expressway. The strength and direction of the wind can lead to changes in the exact sandstorm location. Dust and wind detectors along the rural expressways should be connected with nearby infrastructure and vehicle-based intelligent transportation systems to inform drivers about dynamically changing visibility conditions. Far advance gantries displaying variable speed limits or a sandstorm warning with additional distance indications can optionally be displayed. If the sandstorm moves over the rural expressway sections any nearby VMS should be activated before visibility changes.

Advanced driver assistance systems (ADAS) can play a significant role to inform drivers more accurately and timely about changing visibility conditions along the road. The tested minimum warning distances in this study can also be activated through in-vehicle systems, irrespective of the availability of VMS infrastructure. Moreover, the car icon and language display can be tailored for driver specifically within the vehicle to personalize the warning message.

Concerning the warning design, our study has shown that the sandstorm animation and pictogram warning with explanatory text are similarly effective at the crucial visibility degradation zones. It is expected that the text was effectively transmitting the idea of the sandstorm. However, drivers are not aware of the specific nature of the hazard they are going to encounter in case of a generic hazard pictogram. Therefore, drivers might also look out for additional hazards within the sandstorm affected area. The animated graphic with text on the VMS resulted in more consistent speed reduction percentages within low visibility zones as compared to the pictogram with text on the VMS. Therefore, it is recommended to display a sandstorm animation for expressways with recurring low visibility sections and low traffic densities, whereas a warning pictogram will be more effective for rare sandstorm events on expressways with high vehicle interactions.

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