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Investigating the impact of dynamic merge control strategies on driving behavior on rural and urban expressways – a driving simulator study

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Abstract

Harsh decelerations and abrupt lane changes of drivers on the outer expressway lane in response to merging platoon vehicles from on-ramps increase the crash- and congestion risk on expressways. Several merge control approaches are worldwide implemented. However, there is a gap in knowledge which driving behaviors determine whether a particular merge control approach is best for a rural or urban expressway. This study tests a number of dynamic merge control strategies, such as lane control signalization (eventually combined with variable speed limits (VSL), on a 4-lane urban and rural expressway to measure the behavioral responses of drivers being directly exposed to platoon merging from on-ramps. Subsequently, a comparison was made with the driving behaviors in response to static merge control (e.g. merge warning signs or road marking treatment). The driving behavior of 66 drivers from the State of Qatar was recorded in a driving simulator and analyzed by means of a within-subject repeated measures analysis with univariate statistics. The results suggest that dynamic merge control is more effective for rural expressways considering the higher traffic speeds. The earlier lane changes contributed to smooth maneuvers and gradual speed reductions on the rural expressway and improved safe driving behavior as compared to static merge control. In contrast, the dynamic merge control did not deliver additional safety benefits on urban expressways and can be substituted by a low-cost static merge control approach. Policymakers aiming to improve traffic safety at expressway merging sections are advised to take the speed characteristics of the local expressway into account before implementing dynamic merge control.

Keywords: *Lane control signalization; Dynamic merge control, Driving behavior; Driving simulator; Cooperative lane change*

1. Introduction

On-ramp access points are critical elements of an expressway because on-ramp vehicles have to merge into the expressway stream (Garber & Hoel, 2009). The tapered design of on-ramps (as compared to a parallel ramp design) creates direct interactions between two traffic streams competing for the same road space (Kondyli & Elefteriadou, 2012; Sun, Sun, & Li, 2015). The so-called merging section consists of the through lanes with freeway traffic and the on-ramp acceleration lane with merging vehicles accelerating before merging into the right through lane. Within the merging section, the likelihood of rear-end and sideswipe crashes is increasing as both traffic streams are traveling at different speeds before merging (Liu & Hyman, 2012; Yang & Ozbay, 2011). A study from France found speed differences up to 30 km/h between through and merging vehicles entering the right expressway lane (Louah, Daucher, Conde-Céspedes, Bosc, & Lhuillier, 2011a). Drivers situated on the outer expressway lane are often not prepared to respond in time to these merging vehicles. This can result in harsh deceleration and abrupt lane change maneuvers, which contribute to congestion formation and bottlenecks at on-ramp merging sections.

A traditional merge control strategy is ramp flow control (also known as ramp metering) that uses specialized traffic signals to release vehicles onto an expressway in a smooth and even manner. The goal is to minimize the interference of entering vehicles on the through lane traffic. When ramp meters are coordinated it improves the ability to manage the expressway flow. Flow control can, therefore, limit the number of vehicles entering the expressway and help prevent a flow breakdown, for example by releasing two or three vehicles per green signal at a time. However, in reality, ramp metering can also increase the risk of platoon merging once the released ramp vehicles accelerate on the on-ramp. As a consequence, the ramp vehicles may attempt to force their way onto the expressway. In this case, expressway drivers are reactive since they can either decelerate or move to the inside lane (Kondyli, 2009). Also, the ramp geometry contributes to the issue that vehicles on short on-ramps are not able to attain a speed that is within range of the operating speed of the expressway by the time they reach the point where the left edge of the ramp joins the traveled way of the expressway (Schurr & Townsend, 2010).

Yi & Mulinazzi (2007) conducted field observations on the urban expressway of Kansas city on-ramp merging behavior of vehicles and identified vehicles in platoons as the direct cause of invasive influences on the traffic flow. They defined platoon merge as “a merge situation in which vehicles in a cluster force themselves onto the freeway one after another, ignoring the priority order and instigating invasive influences on freeway vehicles.” (Yi & Mulinazzi, 2007, p. 115). More specifically, they found that the number of evasive events (slow down or change lanes) increases and the standard deviation decreases with the merging platoon size. D’Andrea and Urbani (2001) simulated the driving behavior on tapered on-ramps with a short merge lane in Italy and compared the results with videotaped observations. They found that in the situation of two traffic streams having equal priority the merging drivers were influencing the free-flow traffic. The authors developed a cooperative-competitive behavior model and highlighted that drivers on the right through lane were either responding by making speed and headway adjustments to accommodate the merging vehicle or did a lane change in order to avoid interaction with the vehicles (D’Andrea & Urbani, 2001). Recent literature is further investigating how to increase cooperative lane changes in order to minimize the travel time of mainline vehicles and maximize of the number of merging vehicles (Xu, Lu, Ran, Yang & Zhang, 2019). In this line, several authors made a distinction between the premerge influence area and the merge influence area (Yang, Liu, Chan, Xu, Guo, 2019; Shen, Hu, Sun, & Deng, 2018; Yi & Mulinazzi, 2007). It was stated that drivers were forced to adjust their speed and position according to the merging vehicles within the merge influence area. In contrast, drivers situated in the premerge influence area (300 m before the merge segment) were better able to coordinate the slow down or lane change maneuver to avoid a merging conflict (Yi & Mulinazzi, 2007). Another observational study on driving behavior near on-ramps in Tokyo showed that vehicles on the through lane tend to change to the inner lanes before reaching the merging zone or within the merging zone itself in order to avoid the interaction with the merging vehicles (Sarvi, Kuwahara, & Ceder, 2007). A study from the United States highlighted that a decrease in traffic flow can be expected as a result of abrupt lane changes near on-ramps (Cassidy & Rudjanakanoknad, 2005). In a study by Hill et al. (2014) freeway lane change behavior was analyzed using trajectory data from an instrumented vehicle. It was found that drivers are willing to cooperate with merging vehicles since the driver on the through lane seeks for better driving conditions to gain a speed advantage

(Hill, Elefteriadou, & Kondyli, 2014). This is in line with another study highlighting that expressway drivers would more often cooperate with merging vehicles through lane-changing than through decelerating (Kondyli & Elefteriadou, 2012). Beinum, Farah, Wegman, & Hoogendoorn, (2018) investigated the microscopic characteristics of driving behavior around on-ramps, off-ramps and weaving segments in the Netherlands. They found that abrupt lane changes create turbulence in the traffic flow (Beinum et al., 2018). More specifically, sudden speed reductions or abrupt lane changes are likely to disrupt the traffic flow if drivers are not ready to respond to merging ramp vehicles.

1.1. Dynamic merge control

Latest studies have shown that facilities with ramp metering should also be combined with an additional control approach for expressway drivers (Haleem & Abdel-aty, 2017). Dynamic merge control is a component of Intelligent Transport Systems (ITS) that can be activated to optimize driver performance and operations in real-time (Federal Highway Administration, 2014). Dynamic merge control is a practical approach to handling varying traffic demand on the main lanes and the merge lanes to effectively utilize existing capacity. For instance, the installation of variable speed limits (VSL) activated before merging sections resulted in smoother traffic flows and a reduction of shockwaves (Mccabe, Charton, Riley, & White, 2006; Soriguera, Martínez, Sala, & Menéndez, 2017). Several studies confirm that implementing VSL before merging sections improves the traffic situation compared to applying ramp metering only (Carlson, Papamichail, Papageorgiou, & Messmer, 2010; Xiao-Yun Lu, Qiu, Varaiya, Horowitz, & Shladover, 2014). Research also highlighted that the lane distribution just upstream of an on-ramp can be influenced by using dynamic merge control. For this purpose, dynamic merge control applies lane control signals to close the rightmost motorway lane upstream of an on-ramp to allow ramp vehicles to merge onto the outer expressway lane. European and US guidelines define dynamic lane control as the dynamic allocation of lane access on mainlines and ramps in interchange areas according to the relative demand and traffic volume throughout the day (FHWA, 2016; ERSO, 2018). For on-ramp locations, this may involve a dynamic lane reduction on the mainline upstream of an entrance ramp and/or providing an additional lane for the on-ramp. The lane use on expressways can be dynamically changed based on the real-time and anticipated conditions (ERSO, 2018). It is important that these overhead signs be installed sufficiently ahead of the location to ensure advance warning and lane use indication to drivers (Reinolsmann, N., Brijs, K., Brijs, T., Alhajyaseen, W., Cornu, J., & Mollu, 2018). In particular, a yellow arrow signal is commonly applied to indicate that the driver is advised to execute a lane change as soon as safely possible (Dutta, Venkatanarayana, & Fontaine, 2017; Federal Highway Administration, 2009). A 'keep left' or 'use left-hand lane' message has previously been tested on a variable message sign (VMS) installed upstream on a 3-lane motorway section to see whether the occurrence of congestion at bottlenecks could be delayed (Xing, Muramatsu, & Harayama, 2014). The authors analyzed traffic volume and average speed data and found that the 'keep left' VMS was increasing the average road traffic capacity by 6%, which contributed to a reduced probability of congestion occurrence (Xing et al., 2014). The safety benefits of activating lane control due to changing driving conditions ahead have also been discussed (ERSO, 2018). Moreover, Yan & Wu (2014) reported a VMS influence on the drivers' speed control behavior at 70 m before the VMS location on a four-lane road with a speed limit of 80 km/h. However, studies also point out that the early merge approach should be carefully considered due to possible adverse effects on the expressway capacity (Pesti et al., 2007; Soriguera et al., 2017).

1.2. Static merge control

Static merge warning signs can provide some level of control, often referred to as passive traffic management, since they cannot be altered according to changing traffic conditions. Static warning signs are closely placed to the merge zone itself. The drivers can continue using all lanes but have to be alert to decelerate and change the lane once platoon vehicles merge onto the expressway. This late merge approach stays in contrast to the 'polite' approach of leaving the lane as soon as possible to conduct an early merge maneuver, as it is aimed when activating the dynamic merge control signals (Texas A&M Transportation Institute, 2019). In addition, road markings can complement the static traffic control because they have a guidance function that addresses the lateral position as well as the speed of drivers, e.g. longitudinal and transverse markings (Rao, 2002). A common low-cost approach is the implementation of lane separation markings to manage lane use behavior. For instance, the combined solid and dashed white line can be applied at expressway merging sections to separate the inner lanes and outer merging target lane by indicating the permitted lane change direction (CROW, 2005). Drivers are permitted to first cross the broken, but not the solid, white line next to them to guarantee that lane changes do only occur to the inner lanes of the expressway while vacating the right lane as much as possible for merging vehicles (Federal Highway Administration, 2009). The solid and dashed road marking is implemented at expressway merging sections in some western countries (e.g. A50 in The Netherlands) to facilitate the permitted use of the merge target lane. So far, the application is aimed to keep left lane drivers out of the outer right lane (Rijkswaterstaat, 2017). However, no research has been conducted yet about the behavior of right lane drivers in response to merging ramp-vehicles and the lane crossing indication of the solid and broken road marking.

2. Objectives

Dynamic merge control targeting expressway drivers follows an early merge strategy to vacate the outer right lane for merging ramp vehicles. In contrast, static merge warning signs and road marking treatments are implemented in the vicinity of the merge segment to facilitate late merging based on drivers judgment. Both approaches aim to prepare drivers to safely respond to merging on-ramp vehicles by reducing speeds and changing lanes. The objective of this paper is to investigate the actual behavior of drivers situated on the outer expressway lane being directly exposed to platoon merging vehicles. It is aimed to investigate whether the dynamic merge control using advance lane control signals and VSL improves safe driving maneuvers as compared to a low-cost static warning sign and road marking treatment. More importantly, we are interested in whether there is a difference in dynamic and static merge control approaches if looking at the driving behavior and lane change rate at the on-ramp merge location. Due to the fact that driving speeds and preparedness of drivers to respond to forced platoon merges from on-ramps can vary with the driving environment, we have decided to test these strategies on an urban and rural expressway.

Furthermore, the State of Qatar was selected as the geographical context for this study due to the fact that Qatar is facing major (road) infrastructural challenges in the nearby future (e.g. FIFA world cup 2022). A constant influx of traffic entering from on-ramps of the Doha expressway that connects the FIFA world cup stadiums in the North and South of Qatar will not only put more pressure on drivers to respond to merging traffic but can also increase the occurrence of congestion due to non-optimal lane use at multilane expressway merging sections. Road marking treatments for lane control purposes are available. Also, the Qatar Ministry of Transport and Communications and the Public Works Authority are currently building a vast ITS network of lane-based VMS for traffic operations. However, guidance on how to operate dynamic lane control before merging sections for local expressways is lacking. Besides, its effectiveness with regard to the multicultural and diverse driver population residing in Qatar has not been tested yet. This paper aims to fill this gap in knowledge by investigating the safety benefits of merge control strategies considering the multicultural driving behaviors and perceptions of drivers that determine the response to on-ramp merging vehicles.

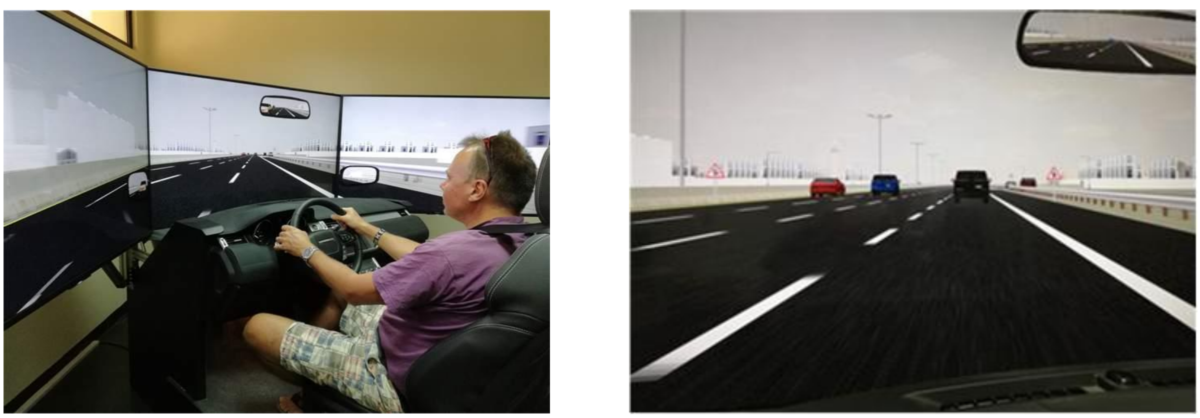
More specifically, our research questions were formulated as follows:

1. Are dynamic or static merge control strategies more effective in preparing right lane expressway drivers to safely respond to merging on-ramp vehicles?
2. How do rural and urban expressway traffic speeds influence drivers responses to the merge control designs?

3. Methodology

3.1. Driving simulator apparatus

Driving simulation makes it possible to study driving behavior in a safe and highly controllable (virtual) environment. New design components can be integrated into simulated expressway scenarios to study driver responses to VMS and road markings in a cost-effective and proactive way. Roadway designs and technologies can be evaluated and improved before implementation in the field, thereby preventing the need for costly curative measures (Bella, 2010). The driving simulator facility at Qatar Transportation and Traffic



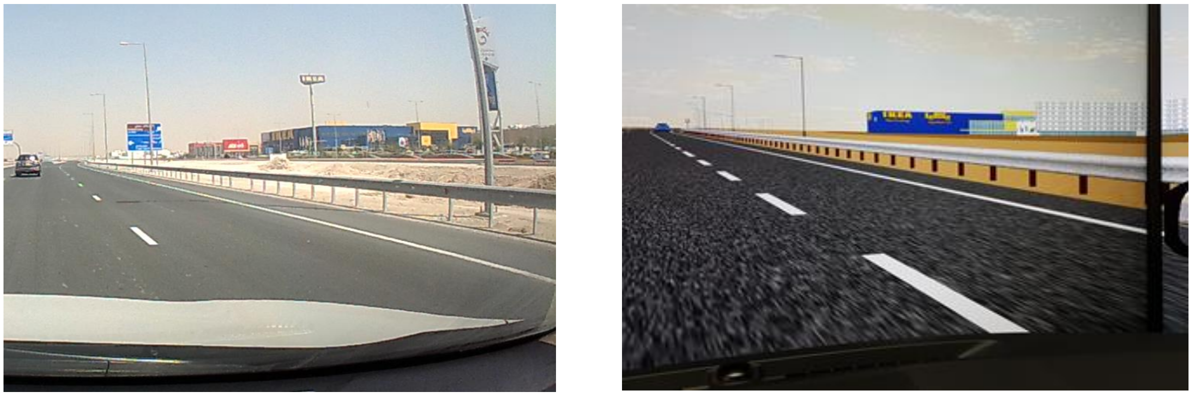
A) Driving simulator B) Screenshot of simulation (urban expressway)

Figure 1: The driving simulator installed at Qatar University

Safety Center (Qatar University) was used for the experimental test drives (Figure 1). The simulator configuration used, consists of two main components: the driving unit – A fixed-base cockpit of a car (Range Rover Evoque) equipped with speedometer, force-feedback steering wheel, pedals, gearbox (automatic transmission), indicators, and three large screen with 135 degree of horizontal field of view, resolution of 5760 x 1080 pixels and a 60 HZ refresh rate. The components are interfaced with STISIM Drive® 3 along with the CalPot32 program which offers high-speed graphics and sound processing. The driving simulator is logging several driving parameters, for instance, longitudinal speed (m/s), deceleration and acceleration (m/s^2) and the lateral driving position, among others.

3.2. Scenario designs and road configurations:

The driving scenarios were designed to replicate the real road conditions in the State of Qatar (see Figure 2). To that end, video footage of the Doha Expressway (urban and rural segments) that were previously recorded, and the Qatar Highway Design Manuals were consulted. The Doha expressway stretches from



A) Real world view of rural expressway B) Driving simulator view of rural expressway

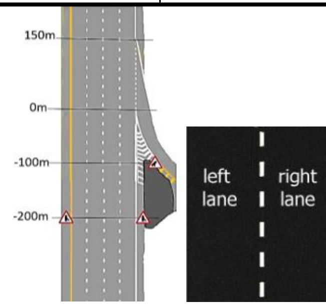
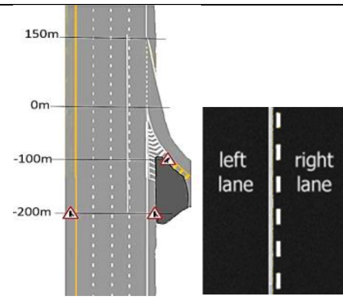
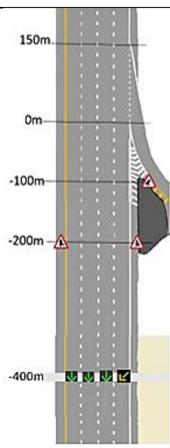
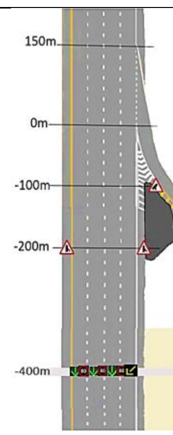
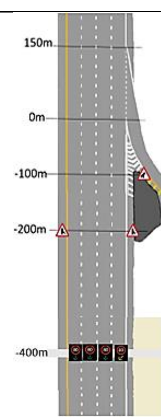
Figure 2: Transition to the rural expressway: real world vs. driving simulator

Doha city to Al Khor in the North of Qatar following an urban and rural environmental transition. A speed limit of 80 km/h is installed on urban expressways due to multiple exit and entrance ramps. A speed limit of 100 km/h is indicated for the rural transitions of the Doha expressway connecting other expressway junctions with off-ramps and on-ramps. The ramp design speed is usually 80 km/h and the total acceleration length for incoming vehicles is 245 m. However, the merging segment from the acceleration lane to the expressway accounts for only 150 m, which is the minimum design requirement as specified by Qatar Ministry of Transport (2015). Typically, two merging warning signs (W113-R, W114-L) are installed along the roadway to control for traffic entering the main roadway of an expressway via the entrance ramp. The warning signs are used for both traffic streams traveling in the same direction and of equal priority merge (e.g., at a slip ramp joining the main roadway). Sign W113-R is located on the main roadway 200 m before the merge segment to warn for traffic joining from the right. Sign W114-L is located on the minor roadway to warn for merging into the mainstream in about 100 m. Both signs are provided on each side of the roadway (Qatar Ministry of Transport and Communications MOTC, 2015). The expressway is characterized by four driving lanes in each direction with a lane width of 3.65 m. The shoulder width accounts for 3 m and the center median separating the driving directions is 4 m for the urban expressway and 10 m for the rural expressway. Vehicles in the simulated environment were created for each driving direction. An 18 km long simulator drive was created starting from the urban expressway, which continued to the rural expressway. Four on-ramps were implemented at varying locations (1.9 km, 8.3 km, 12.9 km, and 17.3 km) along the drive. A second simulator drive with a length of 16.6 km was also designed to simulate the driving direction from the rural expressway towards the urban expressway. Three on-ramps were also implemented at varying locations (9.1 km, 13.6 km, and 15.5 km) along the drive. The distances between merging sections were long enough to ensure that there is no overlap in the influence areas of merging sections. Besides, the driving environment was designed according to the real-life urban and rural driving conditions including standardized exit ramps (before all driving scenarios) and guard rails.

3.3. Driving scenarios

Four driving scenarios were developed for the rural expressway and three driving scenarios for the urban expressway. The drivers were exposed to all scenarios in a total of two separate simulator drives. In one experimental drive, participants had to drive on an urban expressway (normal speed limit of 80 km/h) and continued their way to the rural expressway (normal speed limit of 100 km/h). In another experimental drive, the participants drove back from the rural expressway and faced a transition to the urban expressway.

Table 1: Driving scenarios

	Urban expressway 80 km/h	**Rural expressway 100 km/h**
Static late merge control	1) Urban Control scenario 	24) Rural Control scenario
	32) Urban road marking scenario 	45) Rural road marking scenario
Dynamic early merge control	 53) Lane control scenario 	 6) Lane control with general VSL scenario 
		 7) Lane control with lane-specific VSL scenario 

Two test conditions and one control condition were counterbalanced on the urban expressways and three test conditions, as well as one control condition, were counterbalanced in the rural expressway environment to reduce learning effects. Also, the order of both test drives was counterbalanced across participants. Filler pieces with buildings and road curvature were added to create a realistic and appealing driving experience. Gantry-mounted VMS were installed for the dynamic merge control scenarios to manage the individual lanes from 400 m before the on-ramp location. The legibility distance of the gantry signs is additional 400 m (Margison, 2008). No additional VSL were applied for the dynamic merge control on the urban expressway since both, the on-ramp speed and the mainline expressway speed were set to 80 km/h. In order to reduce the approaching speeds of drivers on the rural expressway (speed limit of 100 km/h) to the merging speed of the platoon vehicles on the on-ramp, additional VSL displaying 80 km/h were installed on the gantry in combination with lane control signals. For this purpose, two design approaches were selected: 1) lane control signals with general VSL being installed between the lanes and 2) lane control signals with lane-specific VSL that are integrated into the same lane control panel. Both approaches are currently in use according to preferences. For the "general VSL" approach, the yellow lane change advise is bigger and therefore, better visible from a distance, whereas the "lane-specific VSL" approach is directly addressing the speed of the driver on the lane below and advising a lane change with a smaller yellow arrow signal.

Table 1 summarizes the seven conditions tested in the simulator: Three urban expressway scenarios with a normal speed limit of 80 km/h: 1.) urban control scenario, 2.) urban road marking treatment, 3.) Lane control VMS without VSL (no change in speed displayed). Four rural expressway scenarios with a normal speed limit of 100 km/h: 4.) rural control scenario, 5.) rural road marking treatment, 6.) lane control VMS with general VSL 80 km/h, 7.) lane control VMS with lane-specific VSL 80 km/h). Besides, Table 1 visualizes the standard road configuration for urban and rural expressways in Qatar with merge warning signs before the merging section and the additional treatment options. The scenarios were designed so that participants would always experience a merge conflict with two platoon vehicles (followed by a third on-ramp vehicle that would merge behind the driver). The platoon vehicles were triggered to start merging onto the outer expressway lane every time when the participants approached the on-ramp locations. Furthermore, the number and position of vehicles on the through lanes of the expressway were kept constant starting from one km before the on-ramp location. Therefore, we controlled for the overall traffic condition and density before and at the merging section to make sure that the traffic interactions on mainlines and on-ramps were standardized for all scenarios.

3.4. Selection of driving parameters

A set of driving behavior parameters was recorded and analyzed, namely, mean driving speeds, mean longitudinal acceleration/deceleration (long Acc/Dec), mean lateral lane position, and variations in lateral acceleration/deceleration of drivers approaching the merge influence area with or without treatments. Mean speed [km/h] is typically a selected safety-related indicator due to its positive relationship with crash risk (Elvik, 2009). Mean long Acc/Dec [s/m^2] provides more insights into the degree to which drivers are able to keep variations in speed under control. When drivers abruptly change their speed, the time to anticipate and/or respond decreases, which might result in an increased risk for rear-end collisions (Ariën et al., 2013). Lane changes prior to the merging segment were analyzed by means of the mean lateral position [m] of the drivers. This parameter is frequently used in the literature to indicate the overall trend in lane position on multilane expressways (Ariën et al., 2016). Furthermore, the standard deviation of lateral acceleration/deceleration [m/s^2] (SD of lateral Acc/Dec) was measured to assess the homogeneity of lane change maneuvers among drivers. High standard deviations indicate abrupt lane changes and high variations in lateral movements among drivers that affect the homogeneity of the traffic stream. Also, the number of cooperative lane changes finalized at the critical on-ramp location was investigated to determine the risk of conflicts with the merging platoon vehicles on the right expressway lane. Last but not least, the minimum time to collision (TTC_{min}) to surrounding vehicles was used to investigate the chance of a conflict with vehicles on the expressway. TTC_{min} is the lowest TTC-value that is calculated by means of the relative distance between two vehicles and their relative speed. The lower the TTC_{min}, the larger the chance of a collision to occur (Polders et al., 2015).

3.5. Participants

Seventy-two drivers were recruited for this study within the State of Qatar. To resemble the mixed population composition in Qatar, a random sampling approach was applied that first started with a convenience sample and was extended to different population groups. The inclusion criterion was a valid driving license permitting to drive in the State of Qatar. Initially, the recruitment took place among students, staff, and workers at Qatar University through posters, circular emails with an online registration link and face-to-face recruitment on campus. Subsequently, the general driver population in Qatar was addressed via information leaflets distributed at different public events in Qatar, online information portals and social media. Up to six participants were tested per day during a one-month data collection period.

3.6. Procedure

The participants were requested to complete a questionnaire to collect data on their socio-demographic background and car usage. An informed consent form was signed and further information was provided about simulation sickness and the possibility to abort the experiment at any time if needed. During a short pre-experiment, participants were tested for their knowledge and understanding of the meaning of the road markings and signage targeted in this study. The correct answers were provided right afterward to ensure that all drivers would have an accurate understanding of the tested intervention designs. This was to reduce bias by lack of knowledge regarding the tested signage. Participants received an explanation about the simulator and a practice drive of 5 minutes allowed them to get used to the simulator and its driving controls (Underwood, 2005). All participants had to confirm whether they felt sufficiently familiarized with the simulator before starting the experimental drives. In this study, we were mainly interested in the driving behavior of participants situated in the right lane when approaching a merging section on the expressway. Therefore, participants were given the following instruction: “The speed limit on the urban expressway is 80 km/h and the speed limit on the rural expressway is 100 km/h. Drive as you would normally do on the expressway but follow the ‘keep right’ law.” Due to the fact that a realistic traffic density was programmed on the left expressway lanes, it was permitted for the drivers to drive faster than the left lane drivers, if they would normally do so. Two test drives of different lengths, each containing three till four merging segments were then presented to every participant. It took about 25 minutes to complete both experimental drives. Afterward, additional information was collected via computer-based questionnaires using Qualtrics, to ask drivers about their sign comprehension, intervention preferences, and reported lane change behavior. Scenario screenshots in Qualtrics were used to let participants recall and evaluate the interventions.

3.7. Data analysis

Driving parameters were recorded for less than every ten milliseconds in the simulator (0.0995 sec). To collect data at every frame of the simulation set, the data save increment should be slightly lower than the simulation frame time to overcome round off errors and slippage in the timing increment (Systems Technology Inc. (STI), p.124). The analyzed road segments were of equal size and stretched from 800 m before the on-ramp entrance until 250 m after. Point-based and zonal based data were extracted using the piecewise linear interpolation technique for every 50 m to assess the parameter values at specific locations such as the VMS gantry installation, the location of the merge warning signs, and the entrance point to the merge segment. A within-subject repeated-measures ANOVA was applied due to the fact that every participant was exposed to all presented conditions.

Four participants did not complete the full set of test drives due to simulator sickness. Additionally, two outliers were detected in the mean speed data set. For this, mean speed box plots were analyzed for every condition. If the average speed in at least one test condition exceeded three standard deviations from the sample mean, the driver was identified as an outlier and thus excluded from analysis. After outlier removal, sixty-six participants remained in the study sample for further analysis. In total, 29 different nationalities participated with almost half of the sample being drivers of Arabic origin, including Qatari drivers. Slightly more than half of all participants were Non-Arabs, which correspondents with the high number of Non-Arabs holding an active driving license in the State of Qatar (Ministry of Interior, Police Department, 2017). The sample consisted of 60% male drivers and 40% female drivers with an age range of 19 to 57 years and an average age of 30 years. Thirty-two percent owned the Qatari driving license B for more than 2 years while 68% of drivers for less than 2 years. The majority of drivers were employed (68%), 28% were students and 4% were under sponsorship. Almost half of the participants drove on average 10,000-20,000 km per year.

4. Results

Twenty-two measurement points were analyzed in 50 m intervals over a travel distance from 800 m before to 250 m after the on-ramp in seven conditions (four for the rural expressway, and three for the urban

Table 2: Multivariate test: within-subjects main and interaction effects

MANOVA Effect	F	dfs	p	η2
Condition	22.835	24, 1351	**<.001**	**.257**
Points	40.556	96, 6170	**<.001**	**.384**
Condition x points	5.170	576, 37421	**<.001**	**.074**

Significance level α = 0.05

Table 3: Repeated measures ANOVA: within-subjects effects on driving parameters

Within-Subjects Effects for condition x points (Greenhouse-Geisser)				
Effect	F	dfs	p	η2
Mean Speed	7.016	14.144	**<.001**	.097
Mean Lateral Position	7.825	14.374	**<.001**	.107
Mean Long Acc/Dec	3.499	21.825	**<.001**	.051

Significance level α= 0.05

Within-Subjects Effects for condition x zones (Greenhouse-Geisser)				
Effect	F	dfs	p	η2
SD Lateral Acc/Dec	3.950	14, 191	**<.001**	.057

Significance level α = 0.05

expressway). Three additional measurement points up to 950 m outside the pre-merge influence area were added in the data visualization since they are at the level of the standardized exit ramp that was set between the filler piece and the analysis zone. It should be noted that the VMS gantry (tested in some conditions at 400 m before the on-ramp) would only become visible at 800 m before the on-ramp location. The data were analyzed by means of a within-subject multivariate analysis of variance (MANOVA). Additional ANOVA's and posthoc tests were conducted for the parameters mean speed, mean lateral position, mean Long Acc/Dec. Zonal-based data of 50 m (between the points) were used to calculate the SD of Lateral Acc/Dec. For all analyses, the p-value was set at 0.05 and ANOVA's were corrected for deviation from sphericity (Greenhouse-Geisser epsilon correction). The analysis results are summarized in Table 2 and Table 3. The multivariate statistics showed significant main effects for the factors condition and measurement points. In addition, a significant interaction effect of condition × points was found (see Table 2). Significant within-subject effects were found for the driving parameters mean speed, mean lateral position, mean Long Acc/Dec and SD of Lateral Acc/Dec (see Table 3), indicating that the four driving parameters significantly varied across the measurement points or zones in function of the different test conditions.

4.1. Mean speed & longitudinal acceleration/ deceleration

Mean speeds (for each condition) were plotted as a continuous series of points and visualized in Figure 3. The entrance of the on-ramp location is indicated by a grey vertical line at point 0 m. The black bold line at -400 m indicates the position of the lane control signalization gantry (in case applied) and the passive control or road marking treatment (if applied) would start at 200 m before the on-ramp location. Figure 3 shows that the mean speeds for conditions on the rural expressways can be grouped together as well as the mean speeds of conditions on the urban expressway. It appears that participants' mean speeds before 850 m before the on-ramp merge influence area vary with slightly higher initial speeds for the rural road marking condition. However, the differences in approaching speeds were insignificant between all rural conditions

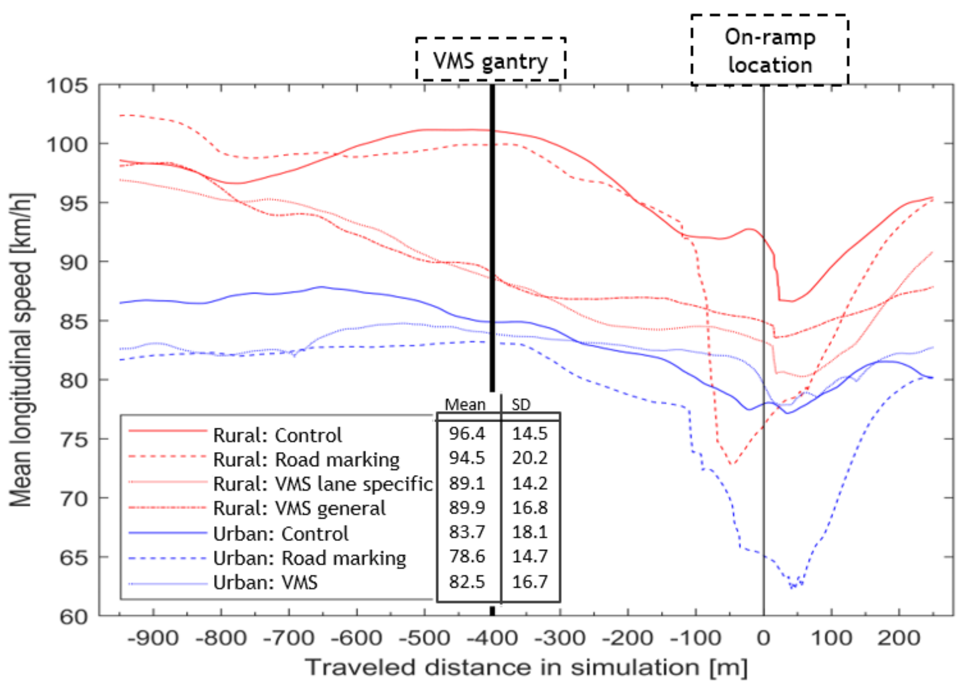
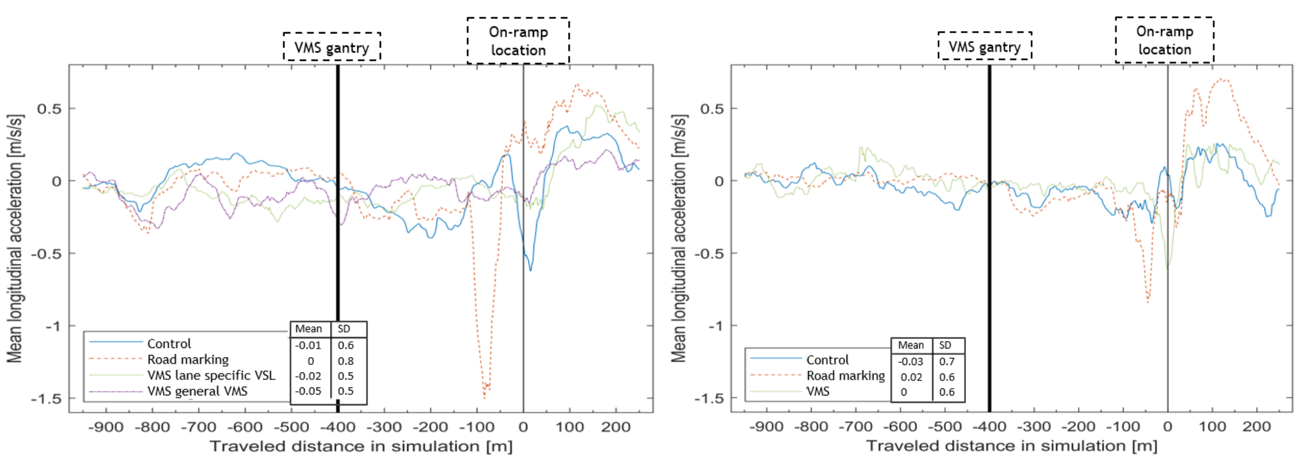


Figure 3: Mean speed for all conditions

at 800 m before the merging section (start of the analysis zone). Afterward, participants started to increase speeds (up to 101 km/h) until 400 m before the merging section in the rural control condition. This was also followed by an increase in driving speeds to 99.9 km/h in the rural road marking condition at 400 m before the on-ramp. Different from that, the VMS lane-specific condition (88.5 km/h) and the VMS general VSL condition (89 km/h) showed a continuous reduction in mean speed from upstream until reaching the rural expressway on-ramp merge point. In contrast, the mean speed profiles for the urban expressway conditions show insignificant differences with very similar mean speeds at 400 m before the merging entrance: 84.9 km/h in the urban control condition, 83.1 km/h in the urban road marking condition, and 83.9 km/h in the urban VMS condition.

Post-hoc tests revealed that there was a significant difference in mean speed between the dynamic and static merge control strategies on the rural expressway. The rural control and rural road marking condition were quite similar, but both also very different from the two rural VMS scenarios. The rural control condition (~98.2 km/h) and road marking condition (~98.5 km/h) followed the same mean speed trend up to 100 m before the on-ramp merge point. A significant and abrupt speed reduction was then occurring in the road marking condition 50 m before new vehicles merged onto the lane at the on-ramp merge point (~76.1 km/h; $F_{(4,241)}$ =13.4, p<0.01). Data for mean Long Acc/Dec in the rural conditions, as shown in Figure 4, confirms that the highest mean deceleration (-1.4 s/m^2) was measured between 100 m and 50 m before the on-ramp merge for the rural road marking condition. Post-hoc tests for 100 m before the on-ramp merge showed a significant difference for mean Long Acc/Dec across all participants for the road marking condition ($F_{(2,159)}$ =7.3, p<.05) on the one hand, and the rural control condition (-0.02 s/m^2), the VMS condition with lane specific VSL (-0.02 s/m^2), and the VMS condition with general VSL (-0.11 s/m^2) on the other hand. This indicates that the drivers stayed on the right lane and reduced their speed abruptly to the same level of the merging vehicles instead of initiating a lane change. Moreover, in the rural control condition we observed significantly higher mean speeds (96.4 km/h) as compared to the two rural VMS conditions (VMS lane specific VSL: 89.1 km/h & VMS general VSL: 89.9 km/h). More specifically, at 400 m before the merging section (location of the VMS) significant mean speed differences of 12.1 km/h were found between the VMS general VSL condition and the control condition $F_{(5,314)}$ =26.8, p<0.01), whereas mean speeds were reduced by 12.5 km/h in the VMS lane specific VSL condition as compared to the control condition ($F_{(5,314)}$ =26.8, p<0.01). Both VMS conditions followed a similar mean speed trajectory (~92 km/h)



A) Mean Long Acc/Dec for the rural conditions

B) Mean Long Acc/Dec for the urban conditions

Figure 4: Mean Long Acc/Dec

and were significantly different from the control condition (~99 km/h) until 200 m before the merging entrance ($F_{(5,339)}$ =20.6, $p<0.01$) as shown in Figure 4. However, at 150 m before the on-ramp, participants drove at significantly lower mean speeds in the VMS lane specific condition (~84.2 km/h) as compared to the rural control condition (~93.6 km/h), and the rural road marking condition (~94.2 km/h) ($F_{(5,331)}$ =16.8, $p<0.01$). The VMS with a general VSL condition (~86.9 km/h) showed a significant difference only with the rural road marking condition but not with the control condition. Interestingly, we also established a significant difference between the rural control and road marking condition at the on-ramp merge point itself ($F_{(4,254)}$ =4, p =.04). More in detail, we observed a deceleration of -0.43 s/m^2 at the merge point of the on-ramp for the rural control condition, whereas an acceleration of 0.37 s/m^2 occurred for the rural road marking condition. This indicates that the lane change maneuver was already initiated in the rural road marking condition, probably to compensate for the loss of speed (indicated by the earlier deceleration peak) when allowing on-ramp vehicles to merge onto the lane. The values for mean Long Acc/Dec in the two rural VMS conditions showed fewer fluctuations and thus appeared to be more stable. This was the case, probably because participants complied with the lane change and the speed reduction advice offered.

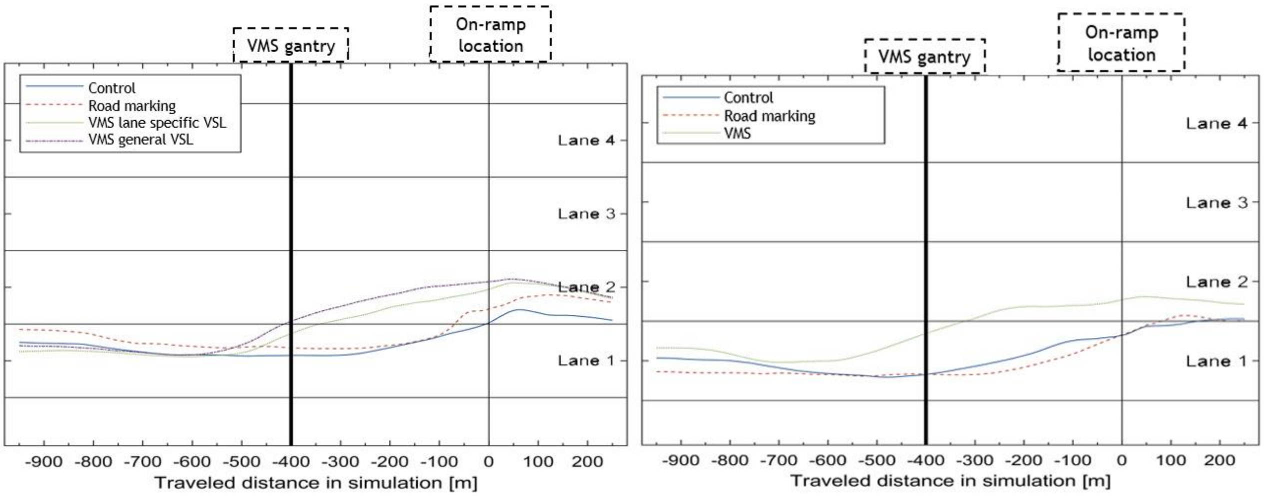
As for the urban expressway environment, mean speeds in all conditions decreased after passing the merging warning signs located 200 m before the on-ramp merge point. However, in the urban road marking condition, participants decreased their speed much stronger, especially within the road marking zone itself. In the segment from 100 m before the entrance point to the on-ramp merge point, there was a significant difference between the mean speeds in the road marking condition and the mean speeds in the VMS condition where drivers changed the lane to maintain their driving speeds. More specifically, 8.5 km/h lower mean speeds were recorded at 100 m before the merging entrance ($F_{(5,324)}$ =12.6, $p<0.01$), 12 km/h lower mean speeds were recorded at 50 m before the merging entrance ($F_{(4,241)}$ =13.4, $p<0.01$), and 14.5 km/h lower mean speeds were measured at the on-ramp merge point ($F_{(5,301)}$ =18.3, $p<0.01$). This can be explained by the fact that participants didn't change lanes but remained in the right lane while reducing their speed for merging on-ramp vehicles. Once the incoming vehicles finished their merging maneuver, a substantial increase in mean driving speed was observed in the middle of the merging segment due to overtaking. Interestingly, more homogeneous profiles for mean driving speeds were found for the urban control condition and the urban VMS condition. At the ramp location itself, insignificant driving speeds of 79.6 km/h in the VMS condition and 78 km/h for the control condition were measured.

Furthermore, starting from 500 m before the merging section, we observed no significant differences in mean speed between the urban expressway VMS on the one hand, and the two-lane control VMS with additional VSL (lane-specific and general) on the rural expressway on the other hand. In line with this, posthoc tests for mean Long Acc/Dec for the urban expressway conditions revealed that there were no significant differences between the urban control, road marking and VMS condition.

It can be concluded that the lane control signal with VSL (either lane-specific or as general configuration) led to significantly lower mean speeds among drivers on the rural expressway when entering the merging section. Mean speeds were effectively reduced to 83 km/h at the on-ramp entrance. Moreover, the implementation of dynamic merge control could improve smooth longitudinal decelerations among drivers on rural expressways who approach merging sections with higher mean speeds as compared to the urban expressway.

4.2. Lateral position & maneuvers

The mean lateral position on the rural and urban expressway was plotted in Figure 5. We can derive from these plots that the average driver in our study was approaching the merge influence area from the right lane



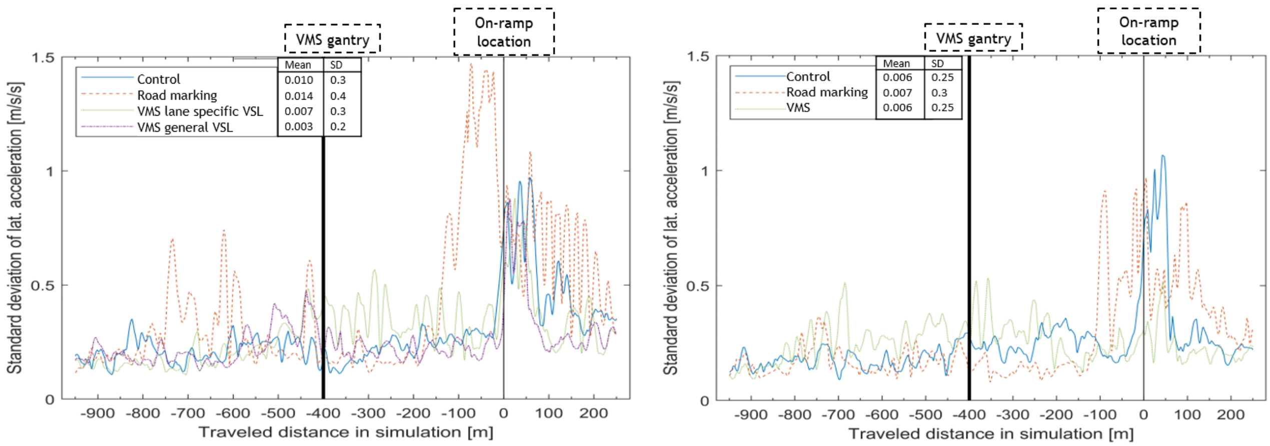
A) Lateral position on rural expressway B) Lateral position on urban expressway

Figure 5: Drivers' mean lateral position

due to higher traffic densities that were simulated on the left lanes. In the rural expressway control condition (Figure 5A), the mean lateral lane position changed from 150 m before the merging section (i.e. after the merge warning signs) till point 0 m (i.e. start of the merging section) to clear the right lane. There were no differences between the control condition and road marking treatment, despite the fact that drivers' mean lateral position in the road marking condition changed slightly earlier to the left lane before the merging section entrance. Contrary to that, the two VMS conditions on the rural expressway showed significantly different results, when compared with the control and the road marking conditions. In the VMS general VSL condition, participants initiated the lane change maneuver already at point 450 m before the merging section (i.e. 50 m before the VMS gantry), which was confirmed by a statistically significant difference in mean lateral position between the control condition and the VMS condition with a general VSL ($F_{(4,284)}$ =37.5, p=0.04). In the VMS condition with a lane-specific VSL, the lane change maneuver was initiated at 400 m before the merging section i.e. the location of the VMS gantry, which was also statistically significantly different from the control condition ($F_{(4,286)}$ =41, p=.046). Overall, both VMS lane change plots follow a quite similar path and are smoothly conducted over the whole distance from their point of initiation to the merging section.

When turning to the mean lateral position in the urban expressway control marking conditions (Figure 5B), we can see similar trajectories that changed just before the merging section. The plot for the urban VMS condition indicates a substantially different trajectory. In this condition, the post hoc tests revealed a significant difference in mean lateral position from 500 m before the merging section as compared to the urban expressway control condition ($F_{(4,273)}$ =36.9, $p<0.01$).

Furthermore, SD of lateral Acc/Dec was calculated based on 50 m segments and plotted to gain deeper insights into the level of lateral acceleration and homogeneity among drivers who conducted lane changes to the left. Results for the rural conditions and the urban conditions can be consulted in Figure 6. As for the rural expressway conditions (Figure 6A), substantially high values for SD of lateral Acc/Dec were measured for the road marking condition in the zone from 100 m till 50 m before the on-ramp merge point ($F_{(2,138)}$ =12.3, p=.02) as compared to the control condition and the two rural VMS conditions. This indicates that there were high variations in participants' lateral acceleration in the first 100 m to the merging entrance if the road marking treatment was implemented. A higher ratio of abrupt lane changes was recorded before



A) SD of lateral Acc/Dec on rural expressway B) SD of lateral Acc/Dec on urban expressway

Figure 6: Variations in lateral Acc/Dec

the merging section as compared to the control and the two VMS conditions. The relevance of this finding is that this could potentially increase the risk for side-swipe and/or rear-end crashes. However, for the urban expressway conditions, no significant variations in SD of lateral Acc/Dec among the three tested conditions were found.

Overall, it can be concluded that the dynamic merge control strategies using VMS on the rural and urban expressways were most effective to motivate an earlier lane change as indicated by the drivers' mean lateral position. The fact that the lane change initiation point in the urban expressway VMS condition (500 m before the on-ramp) was situated further away from the merging section when compared with the rural expressway VMS conditions with a general VSL (450 m before the on-ramp) and lane-specific VSL (400 m before the on-ramp), could be explained by the higher mean driving speeds on the rural expressway in a sense that drivers were approaching the gantries more quickly, which shortens the reaction time towards the lane control message and thus delays the average lane change initiation point.

4.3. Cooperative lane changes

The maximum likelihood ratio for all valid lane changes from the outer to the inner expressway lanes was calculated in a separate dataset using the 95% confidence interval. Furthermore, the dataset of lateral lane position was examined separately to exclude cases where drivers were not located on the right lane (between -950 m till 250 m) when approaching the merging influence area. The lateral position threshold for completed lane changes to the left lane was identified. Lateral position values that were lower than the threshold were associated with a lane change to the left, whereas higher lateral position values were associated with staying the right lane (no lane change). Cases, where no lane change was conducted, were excluded from this analysis. Table 4 provides an overview of the number of cooperative lane changes per condition. We found a significant difference ($p< 0.001$) between the number of completed lane changes in every condition and the remaining distance to the on-ramp when platoon vehicles merge on the expressway. Unsurprisingly, we found that the dynamic merge control strategies contributed to early lane changes among drivers, whereas the static control strategies led to late lane changes. In order to evaluate whether both merge control approaches reduce the risk of conflict with the platoon vehicles merging on the outer expressway lane, we were investigating the percentages of cooperative lane changes until the critical on-ramp merge. We found that for the VMS general VSL condition, 95% of 63 recorded lane changes were completed until the on-ramp merge point. In comparison, for the VMS lane-specific VSL condition 97% of 61 recorded lane

Table 4: Overview of conducted lane changes before and within the merge on-ramp location

	Rural expressway				Urban expressway		
	VMS general VSL	VMS lane-specific VSL	road marking	control	VMS	Road marking	control
Recorded drives	66	66	66	66	66	66	66
# cooperative lane changes	63	61	53	53	57	47	47
Before on-ramp merge location	95 %	97 %	67.3 %	62.3 %	98%	51.1%	68.1 %
Parallel to on-ramp merge loc.	5 %	3 %	32.7 %	37.7 %	2 %	48.9%	31.9%

changes were completed until the on-ramp location. For the road marking condition, 67.3% out of 53 recorded lane changes were completed until the on-ramp location. In the rural control condition, participants completed 62.3% out of 53 recorded lane changes until the on-ramp. In contrast, 37.7% out of the 53 recorded lane changes in the control condition were finally completed within or after the on-ramp merge to overtake the platoon vehicles.

For the urban expressway conditions we can also see that in the VMS condition, 98% of 57 recorded lane changes were completed until the on-ramp entrance. In the urban control condition, 68.1% of 47 recorded lane changes were completed until the on-ramp entrance, whereas 31.9% of the lane changes were completed within or at the end of the on-ramp, which again, relates to the fact that participants wanted to overtake the platoon vehicles that merged onto the lane. In the urban road marking condition only 51.1% out of 47 recorded lane changes were completed before the on-ramp merge and up to 48.9% of the lane changes were completed within or after the on-ramp location (0 till 250 m).

4.4. Interaction with surrounding vehicles

Interactions with the other vehicles traveling on the expressway were analyzed by means of a separate analysis of TTC_{min} values to all vehicles traveling in the same direction. The TTC_{min} is always generated towards the closest surrounding vehicle in the proximity and provides an indication for the intensity of vehicle interaction at certain points along the traveled distance before the on-ramp. TTC_{min} values to surrounding vehicles have been analyzed starting from 500 m before the on-ramp until the end of the merging section. This distance to the on-ramp has been identified as the earliest lane change initiation point for VMS conditions on the rural and urban expressway, which can potentially cause conflicts with other vehicles in the mainstream. The repeated measures MANOVA revealed that there is a significant interaction effect between the conditions and the measurement points (see Table 5). Additional posthoc tests were conducted to investigate the differences in TTC_{min} with surrounding vehicles on the rural and urban expressway. For the rural expressway, significant higher TTC_{min} values were found at 450 m before the on-ramp for the VMS general VSL condition. A mean difference of up to 8 seconds was measured as compared to the rural control condition ($F_{(2,122)}$ =8.1, p=0.003) and 7.5 seconds as compared to the road marking condition ($F_{(2,122)}$ =8.1, p=0.008), which indicates that drivers were already slowing down before initiating the lane change to the adjacent lane. At 350 m before the merging section, there was also a significant higher TTC_{min} value of 2.91 seconds to surrounding vehicles for the VMS with lane-specific VSL as compared to the road marking condition ($F_{(3,176)}$ =12.179, p=0.001) and 2.14 seconds more as compared to the control condition ($F_{(3,176)}$ =12.179, p=0.018). At 100 m before the on-ramp, a clearly significant difference between the mean TTC_{min} values for dynamic early merge conditions (4.3 seconds for both, VMS general and lane-

Table 5: Multivariate test: TTC_{min} to surrounding vehicles

MANOVA Effect	F	dfs	p	η2
Condition	14.689	4, 244	**<.001**	**.184**
Points	52.625	4, 286	**<.001**	**.447**
Condition x points	5.168	12, 803	**<.001**	**.074**

Significance level α = 0.05

specific VSL) and the passive late merge conditions (2.25 seconds TTC_{min} with an SD of 2.4 seconds for road marking and 2.5 seconds TTC_{min} with an SD of 1.45 seconds for control condition) emerged as the traffic density further increased when on-ramp vehicles enter the mainstream. The SD of TTC_{min} for the road marking treatment is alarming and shows that the risk of rear-end and sideswipe collisions with the surrounding vehicle is increasing.

For the TTC_{min} values to surrounding vehicles on the urban expressway, there was no significant difference between all conditions except for -100 m (and continued to the on-ramp location), where significant higher TTC_{min} of 2.98 seconds was found for the control condition as compared to the road marking condition and 2.76 seconds higher TTC_{min} as compared to the VMS condition. Driving speeds are likely to impact the interaction with surrounding vehicles at that point. This is rational considering the fact that drivers were driving 80 km/h in the control condition, whereas slightly higher speeds were measured in the dynamic early merge condition on the adjacent lane (82 km/h) and significant lower speeds for the road marking treatment (74 km/h) ($F_{(2,117)}$ =6.536, p= .003).

5. Discussion

This study analyzed drivers' behavior regarding dynamic merge control on rural and urban expressways. Different VMS designs using lane control arrows and additional VSL for the rural expressway were compared with low-cost static merge control.

5.1. Rural expressways

Our study showed that the dynamic merge control (yellow arrow lane control signalization with either lane-specific or general VSL) implemented in the pre-merge area helped to improve driving performance by preparing drivers for the event of merging platoon vehicles.

The VMS scenarios with a lane-specific and general VSL resulted in 97% and 95% of cooperative lane changes until the on-ramp merge. Overall, drivers initiated the lane change within 450 to 350 m when dynamic merge control was in place. The TTC_{min} values provide evidence that critical interactions with surrounding vehicles were reduced due to the driver's speed adjustments while taking the opportunity to conduct the advised lane change. Based on the results obtained via the questionnaire, we found that 53% of the participants self-declared they would change lane immediately after seeing the yellow diagonal arrow and 30% of the participants indicated to initiate the lane change after passing the gantry (i.e. at 400 m before the merge zone entrance). The results from the questionnaire also showed that 11.4% of drivers would wait with their lane change until seeing the merging vehicles (i.e. 200 m in advance of the merge zone entrance), which is in accordance with the almost 95% success rate for lane changes before the on-ramp. Only a minority of drivers (5.8 %) indicated they would not change lane at all or wait until the moment where they would be forced to merge onto the adjacent lane. Thus, the reported and objectively measured results for the dynamic merge control are very similar, which is not surprisingly since compliance is a matter of intention (Elliott & Thomson, 2010). Altogether, this implies a high compliance rate (83%) for the yellow diagonal arrow signalization. In particular, more drivers completed the cooperative lane change at an earlier point when exposed to the VMS general VSL design as compared to the VMS lane-specific VSL design, which can be explained through the bigger yellow arrow size that appears to be better visible from a distance as compared to the combined VSL in the lane specific design that displays a smaller yellow arrow. One study found that lane-specific VSL can increase the use of the outside lane near capacity (Knoop, Duret, Buisson, & Van Arem, 2010). We can confirm from a behavioral point of view that the lane specific VSL influences not only the speed but also the tendency to stay longer on the lane. For the static merge control strategies, 32.7% till 37.7% of drivers failed to conduct a cooperative lane change before reaching the on-ramp merge location and were forced to take abrupt evasive actions to avoid a conflict with the platoon vehicles. However, only 17% of drivers had indicated in the questionnaire to wait with cooperative lane changes until the merging vehicles are in close proximity or would not change the lane at all. This suggests that the other half of the drivers unintentionally failed to conduct a safe cooperative lane change due to the inability to adjust their driving behavior in time. This was reflected by higher standard deviations in TTC_{min}, which increases the potential risk for sideswipe crashes on the mainstream.

For the control situation, a speed reduction of only 7% was measured until the on-ramp merge point as compared to the dynamic merge control scenarios that resulted in a moderate mean speed reduction by 14% to 83 km/h despite the earlier lane change. The reduction from 100 km/h to approximately 80 km/h, can help to harmonize the traffic flow on all lanes before the traffic density is further increased by merging vehicles (Strömgren & Lind, 2016). The higher driving speeds in the rural control scenario might also increase the side-swipe crash risk with vehicles on the adjacent lane due to the fact that a fast lane change before the on-ramp location is required to maintain the higher driving speeds. In contrast, a much higher mean speed reduction of 26% with peaks in mean longitudinal deceleration and high variations in lateral acceleration shortly before the on-ramp merge were observed in the road marking condition, which contributed to short headways to the front and lagging vehicles. On-road studies investigating lateral movements of vehicles also confirm that the variation in lateral accelerations are increased if stronger longitudinal deceleration and speed reduction is taking place (Mahapatra & Maurya, 2013). The dynamic merge control approach using VMS prevented abrupt lane changes and strong deceleration, which has often been attributed in the literature for disrupting the traffic flow (Soriguera et al., 2017) while increasing the risk for rear-end collisions (Louah, Daucher, Conde-Céspedes, Bosc, & Lhuillier, 2011a). Both VMS design for dynamic merge control were effectively improving homogeneous and gradual speed reduction on the rural expressway and are, therefore, recommended for implementation.

5.2. Urban expressways

The VMS for dynamic merge control on urban expressways had a similar effect on the driving performance (in terms of mean speed, longitudinal and lateral Acc/Dec) as compared to the static merge control strategies. However, the dynamic yellow arrow was very effective in increasing cooperative lane changes. We can confirm that the yellow arrow signalization contributed to 97% of cooperative lane changes before the urban expressway on-ramp merge. Moreover, we found that lane changes were on average already initiated 500 m before the on-ramp. Furthermore, low mean speeds of 79.6 km/h were recorded at the on-ramp merge point while low max longitudinal deceleration was found for the entire pre-merge influence area, which indicates a stable driving trajectory. Traffic management strategies should be straightforward to reduce variations in driving behavior that is responsible for increased turbulence at freeway junctions with off- and on-ramps (Beinum et al., 2017). The post-experiment questionnaire revealed that 87% of the drivers preferred the dynamic merge control strategy over the control situation to be implemented at merging sections. In contrast, only 30% of drivers stated that the road marking treatment would improve the current situation at merging sections. More importantly, 17% fewer cooperative lane changes were completed before the on-ramp merge location in the road marking condition as compared to the control condition. The broken and solid road marking treatment implemented in this study was installed on the centerline to the higher speed left lanes. It is likely that the solid line next to the broken line provided visual guidance (Rao, 2002) that resulted in the tendency to stay within the right lane until the lane change was inevitable. Therefore, the proposed static merge control strategy (i.e. road marking treatment) on urban expressways did not necessarily motivate drivers to conduct an early cooperative lane change, but the lower approaching speeds on the urban expressway as compared to the rural expressway resulted in more drivers choosing to decelerate. This behavior stands in contrast to driving behavior on rural expressways having higher speed limits. Drivers would more often change lanes than to decelerate to cooperate with merging vehicles (Kondyli & Elefteriadou, 2012). Interestingly, our pre-experiment signal test revealed that 98% of the surveyed drivers were familiar with the solid and dashed road marking in our study and knew that they were allowed to cross the road marking to conduct a lane change to the left. Therefore, this study showed that the purpose of implementing the solid and dashed road marking solely remains in allowing, but not actively motivating right lane drivers to conduct a cooperative lane change. In particular, it was shown that the urban expressway control scenario resulted in 17% more cooperative lane changes as compared to the road marking treatment.

It also remains questionable whether a dynamic merge control is necessary for urban expressways with a normal speed limit of 80 km/h. Lower driving speeds reinforce early lane change if advised by the yellow arrow, which can be counterproductive with respect to the available expressway capacity. Furthermore, the urban expressway control condition served well considering the fact that there were no significant differences in driving performance between the tested conditions on the urban expressway. This means that drivers preferences for dynamic merge control is only reflected by their high lane change compliance without additional safety benefits in terms of driving performance. It has to be taken into account that the urban expressways is often characterized by high traffic volumes with less speed differences between mainstream and merging vehicles. The high compliance to the early dynamic merge control could undermine its benefits (Pesti et al., 2007). Therefore, the static merge control using merge warning signs appears to be most cost-effective on urban expressways also considering the higher implementation costs of ITS.

6. Limitations and future research

The characteristics of the heterogeneous driving population in the State of Qatar (Soliman, Alhajyaseen, Alfar, & Alkaabi, 2018; Timmermans, Alhajyaseen, Reinolsmann, Nakamura, & Suzuki, 2019) have to be taken into account when generalizing the results to other driving populations; nonetheless, this study was able to determine the impact of dynamic and static merge control and the extent to which traffic safety can be improved for drivers on the outer expressway lane being directly exposed to platoon merging vehicles from on-ramps. It should be noted that the average traffic density in merging sections on the Doha expressway was simulated. Free traffic flows or congested conditions have not been tested and would possibly influence the drivers' interaction with their driving environment. Furthermore, the external validity of driving simulators is often discussed in the literature. On-road studies and video-based observations are usually desired to obtain absolute validity about driving behaviors. However, no data collection can take place before the real implementation of the dynamic or static merge control at selected sites. A driving simulator study offers the advantage of evaluating the impact of Traffic Management Systems and selecting the most suitable control designs before real implementation on the road through simulating the driving context in a realistic way. The relative validity of driving simulators has been confirmed by several studies focusing on road designs and driver responses (Bella, 2010; Fisher, Rizzo, Caird, & Lee, 2011). In particular, the full Range Rover cockpit with three screens used for this study has previously been validated with on-road data from the Doha expressway to guarantee the correct perception of longitudinal speeds (Hussain et al., 2019).

7. Conclusion & Recommendations

It can be concluded that the implementation of dynamic control strategies has a better effect on driver's speed reduction and cooperative lane change maneuvers at rural expressway merging sections as compared to static merge control strategies. The yellow arrow signalization equipped with VSL was most effective to let drivers clear the right expressway lane before the on-ramp vehicles merged onto the lane. In contrast, the static merge control designs resulted in a moderate amount of cooperative lane changes with increased risk for conflicts. In particular, the road marking treatment contributed to harsher maximum deceleration and abrupt lane changes shortly before the on-ramp merge location on the rural expressways. It can be summarized that the dynamic merge control was increasing the number of safe lane changes by 35% as compared to the static merge control approaches. Furthermore, abrupt lane changes among mainstream drivers were eliminated, while a gradual and smooth mean speed reduction was achieved to harmonize the driving speeds with the traffic environment. This enables drivers to be better prepared for traffic turbulence caused by merging vehicles, which increases the overall safety in rural expressway merging sections.

No significantly different driving behaviors were found for the dynamic and static merge control on the urban expressway except for much earlier lane change maneuvers in the dynamic merge control condition. It is expected that too early lane changes on the urban expressway would unnecessarily reduce the available road capacity considering the lower approaching speeds on the urban expressway. As a consequence, the untreated urban expressway condition can still be recommended in terms of cost-benefit evaluations. The outcomes highlight the importance of pretesting merge control strategies in the same driving context as they will be implemented.

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References

Ariën, C., Brijs, K., Vanroelen, G., Ceulemans, W., Jongen, E. M. M., Daniels, S., Brijs, T., Wets, G. (2016). The effect of pavement markings on driving behaviour in curves : a simulator study, *0139*(August). https://doi.org/10.1080/00140139.2016.1200749

Ariën, C., Jongen, E. M. M., Brijs, K., Brijs, T., Daniels, S., & Wets, G. (2013). A simulator study on the impact of traffic calming measures in urban areas on driving behavior and workload. *Accident Analysis and Prevention*, *61*, 43–53. https://doi.org/10.1016/j.aap.2012.12.044

Beinum, A. Van, Farah, H., Wegman, F., & Hoogendoorn, S. (2018). Driving behaviour at motorway ramps and weaving segments based on empirical trajectory data. *Transportation Research Part C*, *92*(May), 426–441. https://doi.org/10.1016/j.trc.2018.05.018

Beinum, A. Van, Hovenga, M., Knoop, V., Farah, H., Hoogendoorn, S., Beinum, A. Van, … Farah, H. (2017). Macroscopic traffic flow changes around ramps, (July 2018). https://doi.org/10.1080/23249935.2017.1415997

Bella, F. (2010). Can Driving Simulators Contribute to Solving Critical Issues in Geometric Design? *Transportation Research Record: Journal of the Transportation Research Board*, *2138*(1), 120–126. https://doi.org/10.3141/2138-16

Carlson, R. C., Papamichail, I., Papageorgiou, M., & Messmer, A. (2010). Optimal Motorway Traffic Flow Control Involving Variable Speed Limits and Ramp Metering. *Transportation Science*, *44*(2), 238–253. https://doi.org/10.1287/trsc.1090.0314

Cassidy, M. J., & Rudjanakanoknad, J. (2005). Increasing the capacity of an isolated merge by metering its on-ramp. *Transportation Research Part B: Methodological*, *39*(10), 896–913. https://doi.org/10.1016/j.trb.2004.12.001

CROW. (2015). Richtlijnen voor de bebakening en markering van wegen. (T. T. (Enschede), Ed.).

D'Andrea, A., & Urbani., L. (2001). Modeling Drivers' Behavior on Tapered On-Ramps. *Proceedings of the 12th International Conference on Traffic Safety on the Three Continents, Moscow., Part 3*, 35–46.

Dutta, N., Venkatanarayana, R., & Fontaine, M. D. (2017). Examining Driver Understanding and Effectiveness of Diagonal Yellow Arrow Lane Use Control Signal Indications, 1–17.

Elliott, M. A., & Thomson, J. A. (2010). The social cognitive determinants of offending drivers' speeding behaviour. *Accident Analysis and Prevention*, *42*(6), 1595–1605. https://doi.org/10.1016/j.aap.2010.03.018

Elvik, R. 2009. The Power Model of the Relationship Between Speed and Road Safety – Update and New Analyses (No. 1034/2009). Oslo: Institute of Transport Economics.

ERSO. (2018). Motorways 2018. Retrieved from https://ec.europa.eu/transport/road_safety/sites/roadsafety/files/pdf/ersosynthesis2018-motorways.pdf

Federal Highway Administration. (2009). Manual on Uniform Traffic Control Devices. *Citeseer*, 864. Retrieved from http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:No+Title#0%5Cnhttp://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Manual+on+Uniform+Traffic+Control+Devices#0

Federal Highway Administration. (2014). Active Transportation and Demand Management (ATDM).

Federal Highway Administration (2016). Use of Narrow Lanes and Narrow Shoulders on Freeways: A Primer on Experiences, Current Practice, and Implementation Considerations. Washington D.C: Federal Highway Administration.

Fisher, D. l. ., Rizzo, M., Caird, J. K. ., & Lee, J. D. (2011). *Handbook of Driving Simulation for Engineering, Medicine, and Psychology. CRC Press LLC, Boca Raton, USA – Taylor & Francis Group.*

Garber, N. J., & Hoel, L. a. (2009). *Traffic and highway engineering*. *Usa*. https://doi.org/10.1061/(ASCE)HY.1943-7900.0000746.

Haleem, K., & Abdel-aty, M. (2017). Safety Investigation of Combining Ramp Metering and Variable Speed Limits Strategies on Urban Freeways : A Simulation Study, (July 2016).

Hill, C., Elefteriadou, L., & Kondyli, A. (2014). Exploratory Analysis of Lane Changing on Freeways Based on Driver Behavior. *Journal of Transportation Engineering*, *141*(2006), 1–11. https://doi.org/10.1061/(ASCE)TE.1943-5436.0000758.

Hussain, Q., Alhajyaseen, W. K. M., Pirdavani, A., Reinolsmann, N., Brijs, K., & Brijs, T. (2019). Speed perception and actual speed in a driving simulator and real-world: A validation study. *Transportation Research Part F: Traffic Psychology and Behaviour*, *62*, 637–650. https://doi.org/10.1016/j.trf.2019.02.019

Knoop, V. L., Duret, A., Buisson, C., & Van Arem, B. (2010). Lane distribution of traffic near merging zones influence of variable speed limits. *IEEE Conference on Intelligent Transportation Systems, Proceedings, ITSC*, 485–490. https://doi.org/10.1109/ITSC.2010.5625034

Kondyli, A. (2009). Breakdown probablitiy model at freeway-ramp merges based on driver behavior. Retrieved from http://www.albayan.ae

Kondyli, A., & Elefteriadou, L. (2012). Driver behavior at freeway-ramp merging areas based on instrumented vehicle observations. *Transportation Letters*, *4*(3), 129–142. https://doi.org/10.3328/TL.2012.04.03.129-141

Liu, R., & Hyman, G. (2012). Modelling motorway merge: The current practice in the UK and towards establishing general principles. *Transport Policy*, *24*, 199–210. https://doi.org/10.1016/j.tranpol.2012.07.014

Louah, G., Daucher, D., Conde-Céspedes, P., Bosc, F., & Lhuillier, J. P. (2011a). Traffic operations at an entrance ramp of a suburban freeway first results. *Procedia - Social and Behavioral Sciences*, *16*(October 2014), 162–171. https://doi.org/10.1016/j.sbspro.2011.04.439

Lu, X. -Y., Qiu, T. Z., Varaiya, P., Horowitz, R., & Shladover, S. E. (2014). Combining variable speed limits with ramp metering for freeway traffic control, 2266–2271. https://doi.org/10.1109/acc.2010.5530537.

Mahapatra, G., & Maurya, A. K. (2013). Study of Vehicles Lateral Movement in Non-lane Discipline Traffic Stream on a Straight Road. *Procedia - Social and Behavioral Sciences*, *104*, 352–359. https://doi.org/10.1016/j.sbspro.2013.11.128

Margison, P. (2008). Guidelines for the Location and Placement of Variable Message Signs. Technical Direction for Traffic and Transport. Practitioners, (December).

Mccabe, K., Charton, T., Riley, A., & White, J. (2006). *Linking Ramp Metering and Variable Highway Speed Limits*. *IFAC Proceedings Volumes* (Vol. 39). IFAC. https://doi.org/10.3182/20060829-3-NL-2908.00052

Pesti, G., Wiles, P., Cheu, R. L. (Kelvin), Songchitruksa, P., Shelton, J., & Cooner, C. (2007). Traffic Control Strategies for Congested Freeways and Work Zones, *7*(2), 126. Retrieved from

http://tti.tamu.edu/documents/0-5326-2.pdf
Polders, E., Cornu, J., De Ceunynck, T., Daniels, S., Brijs, K., Brijs, T., … Wets, G. (2015). Drivers' behavioral responses to combined speed and red light cameras. *Accident Analysis and Prevention*, *81*(August), 153–166. https://doi.org/10.1016/j.aap.2015.05.006
Qatar Ministry of Transport (MOT). (2015). Qatar Traffic Control Manual Volume 1 Part 2 General Road Signs, *1*.
Qatar Ministry of Interior (2016). General Administration of Traffic. Retrieved from https://portal.moi.gov.qa/wps/portal/MOIInternet/opendata.
Rao, K. V. K. (2002). Road markings. *Highways*, *71*(3), 32–38.
Reinolsmann, N., Brijs, K., Brijs, T., Alhajyaseen, W., Cornu, J., & Mollu, K. (2018). Variable message sign strategies for congestion warning on motorways-a driving simulator study. *Advances in Transportation Studies – An International Journal*, (45), 77–92.
Rijkswaterstaat. (2017). Kenmerken op HoofdWegenNet.
Sarvi, M., Kuwahara, M., & Ceder, A. (2007). Observing freeway ramp merging phenomena in congested traffic. *Journal of Advanced Transportation*, *41*(2), 145–170. https://doi.org/10.1002/atr.5670410203
Schurr, K. S., & Townsend, D. P. (2010). Acceleration Ramps along High Operating Speed Roadways, *1* (November 2010), 50.
Shen, M., Hu, H., Sun, B., & Deng, W. (2018). Heuristics Based Cooperative Planning for Highway On-Ramp Merge. In 2018 *21st International Conference on Intelligent Transportation Systems (ITSC)* (pp. 1266-1272). IEEE.
Soliman, A., Alhajyaseen, W., Alfar, R., & Alkaabi, I. (2018). Changes in Driving Behavior Across Age Cohorts in an Arab Culture: the Case of State of Qatar. *Procedia Computer Science*, *130*, 652–659. https://doi.org/10.1016/j.procs.2018.04.116
Soriguera, F., Martínez, I., Sala, M., & Menéndez, M. (2017). Effects of low speed limits on freeway traffic flow. *Transportation Research Part C*, *77*, 257–274. https://doi.org/10.1016/j.trc.2017.01.024
Strömgren, P., & Lind, G. (2016). Harmonization with Variable Speed Limits on Motorways. *Transportation Research Procedia*, *15*, 664–675. https://doi.org/10.1016/j.trpro.2016.06.056
Sun, J., Sun, J., & Li, Z. (2015). Study on traffic characteristics for a typical expressway on-ramp bottleneck considering various merging behaviors. *Physica A: Statistical Mechanics and Its Applications*, *440*, 57–67. https://doi.org/10.1016/j.physa.2015.08.007
Systems Technology Inc. (STI). (n.d.). STISIM Drive: Scenario Definition Language Events, 1–140.
Texas A&M Transportation Institute. (2019). Dynamic merge control. Retrieved from http://mobility.tamu.edu/mip/strategies.php
Timmermans, C., Alhajyaseen, W., Reinolsmann, N., Nakamura, H., & Suzuki, K. (2019). Traffic safety culture of professional drivers in the State of Qatar. *IATSS Research*. https://doi.org/10.1016/j.iatssr.2019.03.004
Underwood, G. (2005). *Traffic and Transport Psychology: Theory and Application*. Elsevier.
Xiao-Yun Lu, Qiu, T. Z., Varaiya, P., Horowitz, R., & Shladover, S. E. (2014). Combining Variable Speed Limits with Ramp Metering for freeway traffic control, 2266–2271. https://doi.org/10.1109/acc.2010.5530537
Xing, J., Muramatsu, E., & Harayama, T. (2014). Balance Lane Use with VMS to Mitigate Motorway Traffic Congestion. *International Journal of Intelligent Transportation Systems Research*, *12*(1), 26–35. https://doi.org/10.1007/s13177-013-0067-7
Xu, L., Lu, J., Ran, B., Yang, F., & Zhang, J. (2019). Cooperative Merging Strategy for Connected Vehicles at Highway On-Ramps. *Journal of Transportation Engineering, Part A: Systems*,145(6).
Yan, X., & Wu, J. (2014). Effectiveness of variable message signs on driving behavior based on a driving simulation experiment. Discrete Dynamics in Nature
Yang, B.; Liu, P.; Chan, C.-Y.; Xu, C.; & Guo, Y. (2019). Identifying the crash characteristics on freeway segments based on different ramp influence areas,*Traffic Injury Prevention*,*20:4*, 386-391,DOI:10.1080/15389588.2019.1588965
Yang, H., & Ozbay, K. (2011). Estimation of Traffic Conflict Risk for Merging Vehicles on Highway Merge Section. *Transportation Research Record: Journal of the Transportation Research Board*, *2236*(December), 58–65. https://doi.org/10.3141/2236-07
Yi, H., & Mulinazzi, T. (2007). Urban Freeway On-Ramps: Invasive Influences on Main-Line Operations. *Transportation Research Record: Journal of the Transportation Research Board*, *2023*(2023), 112–119. https://doi.org/10.3141/2023-12