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Investigating the impact of a novel active gap metering signalization strategy on driver behavior at highway merging sections

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ABSTRACT

A safe headway to the lead vehicle is important to reduce conflicts with merging vehicles from highway on-ramps. Previous research has outlined the advantage of gap metering strategies to yield sufficient space to merging vehicles and improve highway capacity during peak hours. However, prevailing gap metering systems fail to indicate the minimum required gap and leave it to the drivers' judgment to adjust their headway. This paper proposes a new Active Gap Metering (AGM) signalization that helps outer lane drivers to adjust their headway to the lead vehicle when approaching highway ramps with incoming vehicles. This AGM signalization represents a combination of pavement markings and an innovative Variable Message Sign (VMS). The AGM system was tested alone and in combination with additional variable speed limits (VSL) in distinct environments of the Doha Expressway in the State of Qatar using a driving simulator. The driving behavior of 64 drivers was analyzed using repeated-measures ANOVA. The results showed that the AGM effectively influenced the drivers' behavior on the right stream lane. Drivers did gradually increase the distance to the lead vehicle, which resulted in optimal headways to merging on-ramp vehicles. Most importantly, the minimum time-to-collision (TTC_{min}) to the merging vehicle was increased by an additional 1–1.5 s as compared to no treatment. The proposed AGM signalization can, therefore, be considered by policymakers to influence drivers' headways at critical merging sections.

1. Introduction

Highway entrance-ramps are major sources of conflicts and vehicle collisions, according to multiple studies (Kononov, Durso, Reeves, & Allery, 2012; Liu & Hyman, 2012; Yang & Ozbay, 2011). Ramp vehicles entering the highway traffic stream can create bottlenecks that temporarily increase the downstream traffic density. In these situations, the interaction intensity between drivers located on the outer lane of the carriageway and ramp vehicles initiating the merging maneuver is increased. A study on the types of ramp-related crashed from the US showed that out of 1050 crashes related to highway

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ramps, 36% were caused when vehicles were merging into the traffic stream from an entrance ramp (McCartt, Northrup, & Retting, 2004). These on-ramp vehicles are particularly posing a risk for highway drivers on the right lane when they merge directly in the prevailing headway between the driver and a lead vehicle since speed and headway adjustments are required to restore a safe headway. However, short headways leave drivers with too little time and space to take evasive actions if an on-ramp vehicle forces a merge maneuver into the outer highway lane (Riener, Zia, Ferscha, Ruiz Beltran, & Minguez Rubio, 2013). Intelligent Transportation System (ITS) strategies for Active Traffic Management (ATM) at merge sections such as ramp metering and Variable Speed Limits (VSL) are available for implementation to control the traffic flow at these sections. On the one hand, ramp metering can improve the merging process by regulating the number of on-ramp vehicles that enter the highway, and on the other hand, VSL can warn drivers of downstream congestion to allow smoother approaching speeds to the merging zone (Carlson, Papamichail, Papageorgiou, & Messmer, 2010; Knoop, Duret, Buisson, & Van Arem, 2010; Xiao-Yun, Qiu, Varaiya, Horowitz, & Shladover, 2010). However, these approaches do not directly control for the spacing of vehicle gaps on the merge target lane (Jin, Fang, Jiang, DeGaspari, & Walton, 2017) and do not control for different car-following patterns that vary across drivers with different personalities and perceptions of safety distances (Kondyli & Elefteriadou, 2012). Therefore, a new Active Gap Metering (AGM) signalization is proposed to address and improve drivers' responses to merging on-ramp vehicles at highway merge sections.

2. Literature review

Traffic flow disruptions on highways do often occur at on-ramp sections, where merging vehicles interfere with the traffic flow (Kononov et al., 2012). Speed differences between the drivers on the mainline carriageway and the vehicles on the acceleration lane are generally observed. For instance, a study from France investigated traffic data from video observations on suburban highways and found that the mean speed of merging cars at their merging location differed 5–10 km/h with the mean speeds measured on the right lane. The mean speed of merging cars just reached the mean speed of through vehicles on the right lane at the end of the on-ramp (Louah, Daucher, Conde-Céspedes, Bosc, & Lhuillier, 2011). Usually, the shortest accepted time (or critical) gap for a car merging into the through lane traffic lies between 0.75 s and 1.0 s, according to a study conducted in the Netherlands (Daamen, Loot, & Hoogendoorn, 2010). However, the size of the minimally accepted gap decreases the closer a vehicle gets to the end of the acceleration lane. The geometric ramp characteristics of the on-ramp are another factor that has to be taken into account. Several studies have reported that vehicles on tapered entrance ramps accelerate more strongly as compared to parallel ramp designs and show aggressive merging maneuvers (Daamen et al., 2010; Kondyli, 2009). A study by Kondyli and Elefteriadou (2012) investigated the behavior of drivers in an instrumented vehicle at highway merging sections and found that right lane drivers were more likely to change the lane than to decrease their speed to allow the merging vehicle to enter the mainstream lane. While such voluntary actions can help with reducing the risk of merging conflicts, they can also cause problems with surrounding drivers who are not able to do a courtesy yield (Jin et al., 2017). More importantly, these situations require sufficient space on adjacent lanes, which will be unlikely when traffic intensities increase. Moreover, the driver on the outer through lane might no longer be able to safely adjust his/her headway to the merging vehicle if a forced merge attempt is initiated within the so-called 'merge influence area', which increases the risk of traffic conflicts (Yang & Ozbay, 2011; Yi & Mulinazzi, 2007). Drivers are abruptly changing their speed or lane position to accommodate the merging vehicles from the on-ramp. In contrast, drivers who find themselves in the 'pre-merge influence area' were able to plan and execute the speed reduction and lane change attempt, which improves cooperation and reduces conflicts with the on-ramp vehicles (Yi & Mulinazzi, 2007). The normal vehicle following behavior will be impaired at the moment when cars from the on-ramp merge into the drivers' headway gap and reduce the prevailing headway to the lead vehicle by half (Marczak, Daamen, & Buisson, 2013). This obliges the driver to decelerate to relax the time headway to the new lead vehicle.

The following headway is the distance or time that elapses when the rear bumper of the lead vehicle passes the same reference object as the front bumper of the following vehicle (Risto & Martens, 2013; Shinar, 2007). Once an on-ramp vehicle has started the merging maneuver, the driver on the right lane must anticipate and respond to the change in headway. In the literature, it is commonly accepted that 2 s is the minimum headway for safe car following (e.g. "two-second rule") (Shinar, 2007) and that drivers with a crash history tend to have shorter headways (e.g., less than 1 s) as compared to crash-free drivers (Michael, Leeming, & Dwyer, 2000). This means that the available time to respond to a merge attempt is severely limited when the distance between the driver and the front vehicle is rather short. Headway information systems, which show the driver the time headway to another vehicle using digital road signs, are occasionally implemented to provide feedback and warning to increase the drivers' current headway (SWOV, 2012).

However, it should be noted that under stable conditions, a short time headway does not immediately result in a dangerous situation in case the lead vehicle travels at a faster or same pace as the following vehicle. If, however, the speed of the lead vehicle decreases, the time to collision (TTC) value between the driver and the lead vehicle can be calculated. Consequentially, an evasive maneuver has to be conducted to avoid a crash (Vogel, 2003). The minimum time-to-collision (TTC_{min}) is a valuable safety indicator to assess the interaction intensity among vehicles that are eventually on a collision course if no evasive actions are taken (Hou, List, & Guo, 2014). Research suggests that lower TTC values correspond to higher conflict severities between vehicles as well as a higher probability of collisions (Svensson & Hydén, 2006). It has been pointed out that the TTC_{min} value is a more meaningful measure as compared to the time headway since the actual occurrence of small

TTC values can vary between different driving locations (Vogel, 2003). According to Martens and Brouwer (2011), TTC values below 1.5 s should be considered critical for traffic safety. This essential cut-off value has been commonly applied and confirmed in the literature (Dijkstra et al., 2010; Morando, Tian, Truong, & Vu, 2018; Räma & Kulmala, 2000). Nevertheless, it is also argued that safety assessments based on TTC alone are not taking into account the driver's delayed responses and actual headways (Kuang, Qu, & Wang, 2015). Therefore, the TTC_{min} should be considered in combination with other measures of headway estimations.

2.1. Headway estimations

A majority of studies have highlighted that drivers have difficulties estimating their headway while driving. Inconsistent results have been attained when drivers were required to estimate a specific time headway. For instance, one study found that drivers' time headway estimates (seconds) expanded with increasing speeds when, in fact, the actual headway became smaller. In contrast, estimations in meters remained constant irrespective of speed (Taieb-Maimon & Shinar, 2001). Taieb-Maimon (2007) conducted a study with instrumented vehicles to compare drivers' headway choice for time-based instructions following the 2-second counting technique or a distance-based instruction. It was found that drivers overestimate their headway using the 2-second rule and that the chosen headway was usually greater for distance-based instruction than for time-based instructions. Furthermore, another study argued that drivers' headway is naturally influenced by the perception of a safe headway and the presence of visual reference objects. Therefore, the authors conclude that a headway that is only derived from a verbal counting technique has its limitations for drivers (Risto & Martens, 2013), which is supported by the literature (Lewis-Evans, De Waard, & Brookhuis, 2010; Taieb-Maimon, 2007; Taieb-Maimon & Shinar, 2001). Therefore, with this paper, we aim to investigate a more visual headway guidance strategy for drivers using the Intelligent Transportation System (ITS) strategies.

Yet, Jin et al. (2017) proposed an advanced gap metering system at highway merging sections and modeled the effects on congestion formation using microsimulations. In their study, a system was applied that requests drivers to leave a gap in the most right lane to yield for merging vehicles. The proposed gap metering sign displayed a square indicating the required gap for on-ramp vehicles. It was also highlighted that when mainline traffic is still at high speed, the gap size may need to be higher to facilitate queueing merging vehicles entering the mainstream traffic flow. The authors found that vehicles merging at the study site had a minor impact on the inner lane and that the best performance was achieved when gap metering was applied on the right mainstream lane. Besides, better results were gained if the compliance rate to the signs was not higher than 20% (Jin et al., 2017). This raises concerns regarding the behavioral aspect of drivers being confronted with a gap metering system. The system already relies on drivers' heterogeneous interpretation of the required spacing for one vehicle to merge in front. Besides, the variability of the human spatial perception, driving behaviors, and motivation for sign compliance can often not be investigated in microsimulation studies. Still, such systems have to be improved in signal design to give appropriate guidance to the drivers.

In many countries around the world, the driver has to maintain an appropriate distance to the front vehicle to avoid a collision in case of unexpected braking or speed reduction. However, this general guideline is often not translated into specific minimum distances or headway times. The specific minimum distances or times tend to vary among countries, with the 2-second rule or the half-distance rule being most commonly enforced in European countries (CEDR, 2010). Currently, there are systems in place that aim to address the drivers' estimation of safe distance headways. At particular locations in Europe, for instance, in the Netherlands and Denmark, some highways have auxiliary markings on the lanes (e.g., chevron arrows), which are used to determine a safe distance during poor visibility conditions. The headway must be adjusted to guarantee that at least two chevron markings are visible between one's vehicle and the vehicle in front (AWV, 2019). There are a few test sites where these markings have been painted on the road to persuade drivers to keep two chevron arrows visible between themselves and the lead vehicle, which should correspond to the distance traveled in two seconds. First evaluations show that the chevron arrows help to provide distance headway estimations that resulted in longer headways (CEDR, 2010; SWOV, 2012). So far, these chevron arrows have not been tested in merging sections, and their impact on drivers' headway adjustments to incorporate merging vehicles, has not been assessed yet.

Other ways of maintaining a safe headway are by using advanced driver assistance systems (ADAS) such as Adaptive Cruise Control (ACC) or Following Distance Warning (FDW). These systems allow for selecting a particular distance headway as well as a specific speed. The system itself can intervene by slightly braking and warning the driver to take immediate action. It was found that ACC and FDW effectively reduce the number of very short distance headways. However, ACC might also increase distraction and attention dedicated to other tasks (Nilsson, Strand, & Falcone, 2013; SWOV, 2012). Moreover, drivers with ACC may spend more time on the inner left lanes than unsupported drivers, which makes them less likely to encounter merging conflicts with on-ramp vehicles. Also, driver acceptance of FDW systems might be affected by a decrease in trust if they gave unreliable warnings. Besides, the auditory warning can be considered annoying by some drivers, and the option to deactivate ADAS diminishes its safety benefits (Regan et al., 2006). Furthermore, a study found that drivers do not trust the capabilities of automation in heavier and complex traffic situations. On the other hand, trust in automation is considerably high in light traffic, where drivers were easily distracted and fatigued (Jamson, Merat, Carsten, & Lai, 2013). This shows that the mix of assisted and unassisted cars on the road, as well as the international background of drivers with different experiences regarding the required minimum distance, has to be addressed and managed intelligently in the future. In particular, at highway conflict points where on-ramp vehicles merge into the mainstream and possibly endanger drivers on the merge target lane. Therefore, the implementation of ATM technologies, such as VMS, remains crucial (Litman, 2018).

2.2. Variable message signs

VMS designs are required that convey a temporary warning message through text and pictograms (i.e., symbols and icons). According to the principles of VMS design, when a pictogram is part of a VMS message, its meaning should not be retaken by text to avoid redundancy (Arbaiza & Lucas-Alba, 2012). However, Koyuncu and Amado (2008) found that the shortest reaction time is observed when a pictogram is displayed with text (Koyuncu & Amado, 2008). Moreover, the combination of pictograms and text increases the correctness and speed of interpretation (Cristea & Delhomme, 2015). Mainly in situations where drivers are not sufficiently familiar with the pictogram, additional text should be provided to make the meaning clearer to all drivers (Shinar & Vogelzang, 2013). Text messages on VMS should have a low number of letters to be understood quicker and instructional messages further increase the compliance of drivers (Hössinger & Berger, 2012).

Driving simulator studies have been conducted in the past to study the effect of control signal designs on human driving behavior. This approach makes it possible to simulate driving behavior in a controlled setting. For instance, a driving simulator study tested VMS to warn drivers of slippery road conditions and minimum headways (Räma & Kulmala, 2000). The VMS was based on a combination of graphics and text (showing the minimum distance in meters) and was turned on when the road conditions were found to be slippery. The results of this study showed a reduction of 1–2 km/h in speed and a reduction in the number of time headways shorter than 1.5 s. The effect was also greater at night and when the sign was flashing. Based on this, the authors argued that the signs are more effective when they are more conspicuous (Räma & Kulmala, 2000). Also, the road sign structure is affecting drivers' behavioral compliance. According to several driving simulator studies (Mollu, Cornu, Declercq, Brijs, & Brijs, 2017; Reinolsmann et al., 2018, 2020), cantilever signs placed on roadside poles resulted in longer viewing times and gazes away from the road as compared to gantry mounted overhead signs. Moreover, gantry signs have the advantage of being in the drivers' field of view and dedicated lane and, therefore, directly relevant to one's behavior.

It can be summarized from the literature that VMS warning should be placed in the pre-merge area of the outer mainstream lane together with visual guidance (e.g., chevron marking) that helps drivers to correctly adjust their distance headway to the lead vehicle. The imminent danger appears when the driver has to adapt his/her car following behavior to on-ramp vehicles that initiate an immediate merge maneuver into the prevailing headway gap. An effective approach is required to prepare drivers to increase their distance headway to the initial lead vehicle to counteract the occurrence of conflicts with merging on-ramp vehicles. Therefore, this study aims to improve the safety and comfort of right lane drivers using an on-road AGM signalization.

3. Objectives

Conventional gap metering systems fail to provide distance references for a safe headway choice and leave it to the drivers' judgment to adjust their headway to merging vehicles. This paper proposes a new Active Gap Metering (AGM) signalization strategy that helps drivers adjust their distance headway to the lead vehicle before approaching the merging section. This AGM signalization represents a combination of paved chevron markings and innovative VMS that can display the required safety distance based on real-time driving speeds and traffic density by displaying the number of chevron markings that have to be visible between the driver and a lead vehicle on the outer lane. The goal of the AGM is to take the limited human capabilities for applying time gap heuristics into account. The driving behavior before merging sections in urban and rural parts of the Doha highway was addressed in this study. Drivers' responses to this new system were measured in a driving simulator to assess the traffic safety impact before its implementation on the road. In this study, the following hypotheses were tested:

H1. The distance headway to the lead vehicle will increase until the merge section if AGM signalization is present.

H2. The distance headway to the merging on-ramp vehicle will be increased if AGM signalization is present.

H3. Critical TTC_{min} values to the merging vehicle will be eliminated if AGM signalization is present.

4. Methodology

4.1. Driving simulator

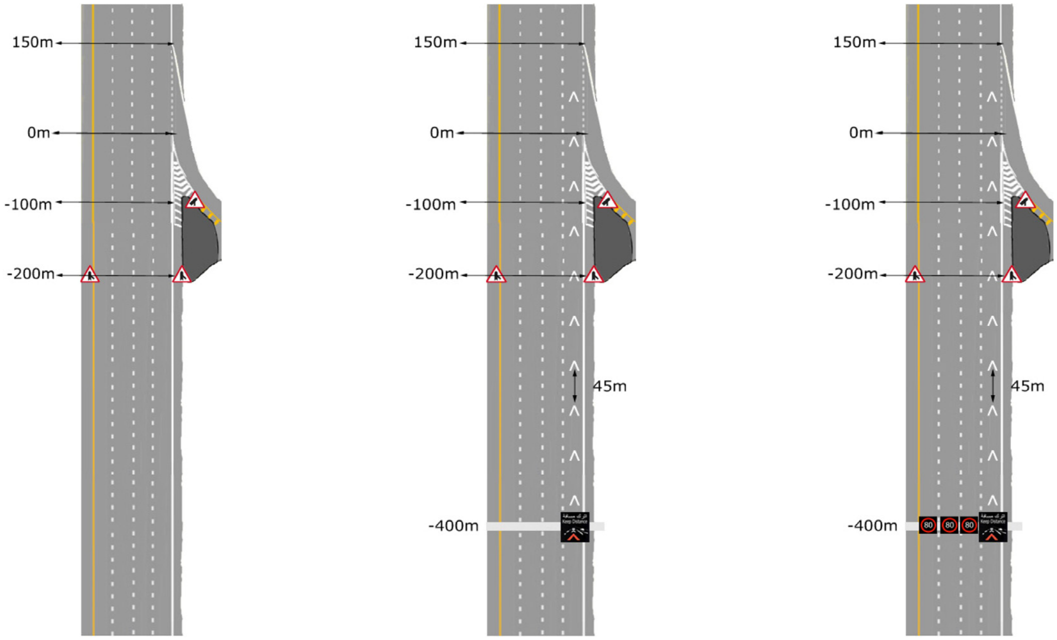
Driving behavior can be studied in a safe, experimental setting using driving simulations. We have proactively investigated the impact of innovative VMS and road markings with the driving simulator at Qatar University (Fig. 1). The medium-fidelity simulator is fixed-based, consisting of a Range Rover Evoque cockpit. The simulator has all required driving

Fig. 1. Driving simulator at Qatar University.

controls for realistic driving and works with automatic transmission accompanied by three large screens with a 135° display area, high resolution (5760 × 1080 pixels), and a refresh rate of 60 HZ to complete the simulation experience. The simulator is programmed with STISIM Drive® 3 and interfaced with CalPot32 to guarantee high-quality images and sound. Several driving parameters can be logged for research purposes, such as driving speeds (m/s), deceleration/acceleration (m/s^2), time to collision values, and lateral driving positions, among others. A previous study was able to confirm the validity of the driving data when comparing on-road data with data collected in the driving simulator present at Qatar University (Hussain, Alhajyaseen, Brijs, et al., 2019). More specifically, observations of speed perception and actual speeds were collected from forty drivers driving in the simulator and an on-road car. The participants were always completing one test drive when the speedometer was hidden, and another test drive when the speedometer was revealed. The drivers were asked to accelerate to four different speeds (50, 70, 80, and 100 km/h) and had to report the moment when they felt to have reached the requested speed. In the meantime, the experimenter was recording and comparing the actual speeds collected with an external high-fidelity GPS. The results of a questionnaire supported a high ecological validity for the physical characteristics of the fixed-based driving simulator at Qatar University (Hussain, Alhajyaseen, Brijs, et al., 2019). Moreover, a comparison between the actual speed observations from the Qatar roads and the simulator was made. The longitudinal speeds and decelerations measured in the driving simulator were also relatively valid compared to the traffic stream data from the local roads and the Doha Expressway (Hussain, Alhajyaseen, Pirdavani, et al., 2019).

4.2. Scenario designs and proposed gap metering system

Video footage of the urban and rural parts of the Doha Expressway was previously recorded to design realistic driving scenarios. The simulated highway was defined according to the Qatar Highway Design Manual and represent four lanes with an individual lane width of 3.65 m and a shoulder width of 3 m. The tested interchanges are characterized by exit and on-ramps that are spaced 3 km or more along the Doha Expressway without creating weaving (Qatar Ministry of Transport & Communication (MOTC), 2015a). It is aimed to demonstrate the idea of a single direction merging problem due to the ramp-lane reduction. The Doha Expressway follows a transition from the urban to the rural environment or from the rural to the urban environment when taking the same highway back to Doha. Therefore, two (both direction) highway drives were simulated with a length of 16 km and 18 km, either stretching from the urban to the rural environment or from the rural to the urban environment. All participants drove the two drive tests, which contain two AGM conditions and one control condition. The AGM condition was tested in one drive test on an urban 80 km/h highway stretch, whereas another AGM condition with an additional variable speed limit (VSL) of 80 km/h was tested on the rural 100 km/h highway stretch of the second drive test. The order of the simulation drives was randomized among participants to avoid order effects. A control condition without the AGM signalization but with the identical vehicle and merging interferences was added on the 80 km/h (urban highway) stretch of the 18 km drive test. It should be noted that the urban and rural parts of the simulated highway have been clearly characterized as being urban (speed limit of 80 km/h; center median of 4 m, buildings, malls, etc.) and rural (speed limit of 100 km/h, a center median of 10 m, sandy desert environment, no buildings), while the traffic density and vehicle interactions remained the same in the conditions. In both drive tests, additional standardized dummy on-ramps without merging interferences from on-ramp vehicles were included in the filler pieces between the conditions to create an appealing and realistic driving experience and to prevent learning effects. Fig. 2 shows the scenario designs for the control condition (A) and the two AGM test conditions (B, C). As can be seen in Fig. 2B–C, the AGM scenarios consist of a gantry-mounted VMS installed 400 m before the on-ramp and several chevron markings (auxiliary markings) that were paved on the rightmost lane. The distance between the chevrons counts 45 m with a length of 4 m for each marking as defined by European



A) Control condition highway (80 km/h)

B) Gap metering for 80 km/h highway

C) Gap metering with VSL 80 km/h for 100 km/h highway

Fig. 2. Overview of control and gap metering test conditions.

standards (AWV, 2019). This distance corresponds to the half-distance rule for safe headways on 80 km/h highway sections (CEDR, 2010).

For the highway on-ramp itself, the Qatar Traffic Control Manual specifies an on-ramp acceleration length of 245 m, of which 150 m tapered length is available for on-ramp vehicles to complete the merging maneuver onto the highway (Qatar Ministry of Transport & Communication (MOTC), 2015a). Approximately 200 m before the on-ramp, two merging warning signs are installed on both sides of the highway to warn for incoming traffic (MOTC, 2015b). An additional merge warning sign is located on the on-ramp itself, addressing incoming vehicles. The on-ramp vehicles appeared at a 200 m distance from the driver and were located parallel to the merge warning signs at 200 m before the actual on-ramp gore nose. The initial driving speeds of these on-ramp vehicles were defined as 60 km/h on the ramp (MOTC, 2015a). These vehicles were programmed to accelerate within 200 m to 80 km/h and to initiate the merge process on the highway. Depending on the drivers' approaching speed, the on-ramp vehicle's acceleration was matched to trigger the action command for the new lateral position and heading angle change (including a transition time) to the outer highway lane to merge in front of the driver. Another on-ramp vehicle would then merge behind the driver.

The proposed AGM signalization was only implemented on the outer lane of the urban highway stretch and accompanied with an additional VSL of 80 km/h for the inner lanes on the rural stretch of the highway to control the traffic flow homogeneity between lanes before the merge section. Applying VSL jointly with another active traffic management strategy when needed was recommended by Soriguera, Torné, and Rosas (2013). The distance headway is signalized with an animation on a VMS showing a sequential loop of flashing chevrons as displayed from left to right in Fig. 3. A graphical image indicating a

Fig. 3. Sequential loop of flashing chevrons on VMS.

merging situation with a lead vehicle and an on-ramp vehicle was combined with the instruction to ‘Keep Distance’ in a bilingual format (i.e., Arabic and English). The flashing chevrons (in red LED) on the VMS refer to the safety distance that has to be maintained to the lead vehicle. The flashing chevrons are a representation of the number of paved chevron arrows on the roadway that have to be visible at all times. Guidelines from a European road authority suggest a minimum distance of 2 chevron markers for highway speeds around 80 km/h (AWV, 2013), which was applied in the AGM test conditions.

In all conditions (including the control scenario), a simulated lead vehicle was encountered at 650 m before the on-ramp location on the outer right lane with an initial headway of 200 m to the driver. The lead vehicle was constantly driving close to 80 km/h. Besides, we have also placed a right lane vehicle with a driving speed of 72 km/h in the filler piece before the beginning of a test scenario to create realistic vehicle interactions. This vehicle can be easily overtaken when driving close to the speed limit. However, it was also intentionally placed on the outer highway lane to account for slower drivers who would not have a meaningful interaction with the faster right lane vehicle in the test zones. These drivers would still have to interact with a lead vehicle on the right lane by adjusting their headway within the tested conditions. Also, additional vehicles were placed on the inner lanes to simulate a realistic traffic density. Once the test condition started, vehicles on the inner lanes were driving with similar speeds, and a close follow distance to discourage drivers from changing lanes before the on-ramp section. All simulated vehicles, including the lead vehicle, did not perform a lane change. The driving conditions were standardized in terms of traffic density and interactions with lead vehicles and on-ramp vehicles.

4.3. Procedure

Participants signed an informed consent, which was previously approved by the ethical committee of Qatar University. The form entailed information about the risk of simulation sickness and the right to end the participation without any reason. The participants started with a pre-quiz that asked them to indicate the meaning of the tested chevron markings and the supplementary VMS. A general explanation of the purpose of the VMS was provided to make sure that the observed driving behavior is not a result of a lack of knowledge. Afterward, a pre-questionnaire was distributed to collect data on the demographic background and driving habits. The participants were then introduced to the driving simulator and had to do a practice drive to get used to the driving controls. Afterward, the two randomized test drives (either starting from the urban to the rural or from the rural to the urban highway environment) were presented, and the participants were instructed to drive as they would normally do on the highway while respecting the ‘keep right’ traffic law. This means that drivers were free to move to the left lanes to overtake slower vehicles, but it was implied to return to the right lane as often as possible. The participants were not informed about possible merging interferences with on-ramp vehicles. Finally, the participants filled in a post-questionnaire to evaluate the AGM signalization scenarios. The entire experiment took one hour for each participant.

4.4. Data collection and analysis

Mean speed (km/h) is an important indicator of safe driving since higher speeds are associated with an increased crash risk (Elvik, 2013). The mean lateral position [m] of drivers was used to measure changes in the continuous lane position on the multilane highway (Ariën et al., 2016). Standard Deviation of longitudinal acceleration/deceleration (SDAD) is an indicator of speed variations and traffic flow homogeneity (Marchesini & Weijermars, 2010). This is particularly relevant for assessing drivers’ speed adaptations towards the lead and merge vehicle. Furthermore, distance headways [in m] to the initial or new lead vehicle (e.g., merging on-ramp vehicle) is an indicator of car-following behavior and provides valuable information about the changes in gap spacing (Risto & Martens, 2013). The distance headway was compared with the distance indicated by the two signalized chevron markings. The STISIM Drive software records a continuous headway distance between the driver and another tagged vehicle in the driver’s path for every time frame. Furthermore, the TTC_{min} [seconds] is used to identify the collision course to the lead and merge vehicle if no evasive action is taken and is an indicator for vehicle interaction intensity (Vogel, 2003). The vehicle interaction intensity, as defined by Laureshyn, Svensson, and Hydén (2010), describes the proximity (in time, space) between two road users approaching each other at any angle, the current speed of the road users, and the intensity of a necessary evasive action (e.g., braking). The simulator updates the simulation screen at a rate of 60 frames per second, and the lowest overall value of TTC per time frame is used to compute TTC_{min} when the driver is on a collision course with another vehicle. Therefore, the TTC_{min} is the minimum time, based on the relative speed between a (merging) front vehicle and the driver, that is left until a collision would occur (see Vogel, 2003; Weng, Xue, Yang, Yan, & Qu, 2015).

The analyzed road stretches per condition always accounted for 1200 m starting shortly before the visibility distance of 500 m to the AGM signalization (if available). Zonal-based driving data were extracted for every 50 m. A within-subject repeated measures multivariate analysis of variance (MANOVA) was applied since all drivers drove through all three conditions (A = Control; B = AGM signalization, C = AGM signalization with VSL) and 24 measurement zones. The parameters ‘mean speed’, ‘mean lateral position’, ‘SDAD’, and ‘mean distance headway’ to the lead and the merging vehicle were further analyzed through post hoc tests. A cleaned dataset of TTC_{min} values was used to conduct univariate statistics to indicate the TTC_{min} to lead and merging vehicles per condition. For all analyses, a Greenhouse-Geisser and Bonferroni correction was applied at a p-value of 0.05 (Field, 2009).

4.5. Participants

Seventy-two drivers in the State of Qatar were recruited for this study. Information leaflets were distributed among drivers at social gatherings and events in Qatar. Also, the link to the registration website to participate in the study was published on social media, websites, and with circular emails from Qatar University. No compensation was offered. The sample resembled the mixed population composition in Qatar. Data of one participant were missing due to simulation sickness, and seven participants were identified as outliers. Drivers were considered as outliers and excluded from the analysis if mean speed deviated three SD from the sample mean (Denker & Woyczynski, 1998; Field, 2009) or if drivers' mean lateral position deviated strongly from the rightmost mean lane trajectory before the start of the analysis sections (i.e., 1000 m before the on-ramp merge location). In total, 64 participants remained in the dataset. Almost 30 different nationalities participated in the study. Half of the drivers had an Arabian background, including Qatari drivers, and the other half came from Asian and Western countries (see Fig. 4). The sample captures the characteristics of Qatar's heterogeneous driver population that have already been discussed in several papers, confirming the unique combination of driver backgrounds and cultures that can contribute to an increased risk of traffic conflicts (Soliman, Alhajyaseen, Alfar, & Alkaabi, 2018; Timmermans, Alhajyaseen, Reinolsmann, Nakamura, & Suzuki, 2019; Timmermans, Alhajyaseen, Ross, & Nakamura, 2020). Generally, 59.4% of male drivers and 40.6% of female drivers were included in the sample. The age ranged from 18 to 57 years, with an average age of 31 years (SD +/-10 years). The majority of participants in this sample are working in Qatar (professionals 68.8%). Most drivers have their driving license for more than two years (82.3%) and drive on average at least 10,000–20,000 km per year (see Table 1).

5. Results

5.1. Driving behavior

The repeated measured multivariate analysis of variance (MANOVA) revealed that the three levels for 'condition' (A, B, C) and the 24 measurements for 'zones' (50 m distances from −950 m to +250 m from the on-ramp location) had significant main effects. Moreover, a significant interaction effect between the factors 'condition × zones' was found (see Table 2).

A repeated measures univariate analysis of variance (ANOVA) was performed to test for significant changes in drivers' mean speed, lateral position, SDAD, and distance headways (see Table 3). The results indicate that mean speed, the lateral position as well as the distance headway to the lead and merging vehicle are significantly different for the tested conditions at a 99% confidence level. SDAD remains insignificant and will not be investigated in more detail.

5.1.1. Mean speeds

The mean speed profiles for active gap metering and active gap metering with VSL 80 km/h were compared with the control condition (80 km/h) and illustrated in Fig. 5. The vertical thick black line at −400 m represents the AGM gantry location, and the vertical grey line indicates the on-ramp location at 0 m. The post hoc tests revealed that there were significantly higher mean speeds for the AGM with VSL ($F_{(2;125)} = 35.25$, $p < 0.001$) as compared to the AGM and control conditions at the very beginning when the gantry becomes visible (zone −900–850 m). This is not surprising since the AGM with VSL 80 km/h signalization was implemented on the 100 km/h rural highway stretch, whereas the AGM signalization and control condition were encountered on an urban highway stretch with a conventional driving speed of 80 km/h. The variable speed limit change to 80 km/h on the 100 km/h rural highway stretch requires a transition time among drivers to adjust their

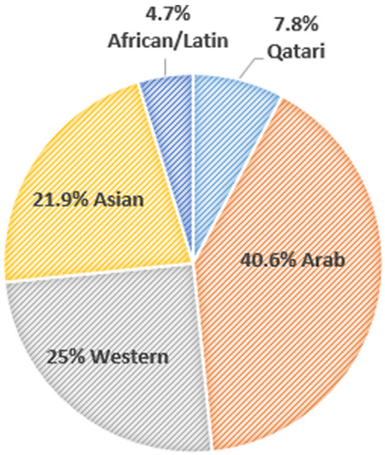


Fig. 4. Drivers' origin (n = 64).

Table 1
Driver characteristics.

Driver sample (n=64)	
Occupation	
Student	26.6%
Professional	68.8%
Unemployed/under sponsorship	4.7%
License ownership	
Driving license B (< 2 years)	17.7%
Driving license B (>=2 years)	82.3%
Annual Driving kilometers	
0 - 10.000 km	23.4%
10.000-20.000 km	45.4%
> 20.000 km	31.2%

Table 2
Repeated measures multivariate test: within-subjects main and interaction effects.

MANOVA				
Effect	F	dfs	p-value	$\eta\rho^2$
Condition	8.075	12; 258	<0.001[**]	0.273
Zone	120.101	138; 8964	<0.001[**]	0.638
Condition × zone	9.414	276; 18,337	<0.001[**]	0.123

[**] Significance level $\alpha < 0.001$.

Table 3
Effects on driving ANOVA: repeated-measures parameters.

Within-Subjects Effects for univariate tests				
Effect	F	dfs	p-value	$\eta\rho^2$
Mean speed				
Condition	21.062	2; 127	<0.001[**]	0.239
Zone	49.070	4; 270	<0.001[**]	0.423
Condition × zone	9.638	6; 424	<0.001[**]	0.126
Mean lateral position				
Condition	0.742	2; 129	0.473	0.011
Zone	30.663	2; 158	<0.001[**]	0.314
Condition × zone	5.653	6; 413	<0.001[**]	0.078
SDAD				
Condition	1.906	2; 131	0.154	0.028
Zone	11.497	6; 387	<0.001[**]	0.146
Condition × zone	1.247	11;709	0.254	0.018
Headway lead vehicle				
Condition	20.972	2; 133	<0.001[**]	0.238
Zone	273.712	1; 74	<0.001[**]	0.803
Condition × zone	15.791	3; 177	<0.001[**]	0.191
Headway merging vehicle				
Condition	27.263	2; 133	<0.001[**]	0.289
Zone	476.442	1; 71	<0.001[**]	0.877
Condition × zone	26.321	2; 159	<0.001[**]	0.282

[**] Significant at $\alpha < 0.001$.

speeds when the AGM with VSL is detected. At the location of the VMS gantry (zone 400–350 m to the on-ramp), it was found that the AGM condition had 10.8 km/h lower mean speeds as compared to the control condition and 6.8 km/h lower mean speeds as compared to the AGM with VSL condition. Speed differences between the AGM with VSL 80 km/h and the control condition were insignificant, which indicates that the AGM with VSL was effectively reducing the driving speeds from 100 km/h to 80 km/h starting already 200 m before the gantry. Similar mean speeds were measured after 600 m before the on-ramp location and continued further. The AGM condition that was implemented on the normal 80 km/h highway showed significantly lower mean speeds (lower by 8.5 km/h) as compared to the control scenario ($F_{(2;117)} = 5.40$, $p = 0.001$) but not significantly different with the AGM with VSL condition.

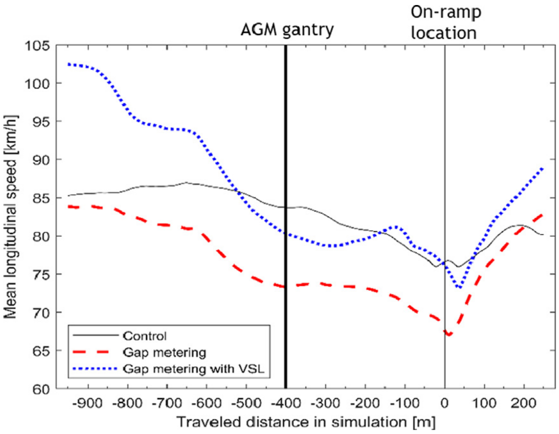


Fig. 5. Drivers' mean speeds in all conditions.

5.1.2. Mean lateral position

Drivers' lateral lane position is displayed in Fig. 6 and shows the three trajectories per condition with reference to the gantry location of the AGM signalization (the vertical black bold line at −400 m) and around the on-ramp location at 0 m (vertical grey line). Post-hoc tests revealed that the lateral driving position for the AGM condition was significantly different at the on-ramp as compared to the control situation ($F_{(2;122)} = 8.73$; $p = 0.001$). The pairwise comparisons indicated a mean lateral position difference of 1.32 m between AGM and control condition, suggesting that drivers remain longer on their initial driving course when approaching the merge section. In contrast, a lane change initiation has already taken place in the control condition. The lateral position in the AGM condition was significantly different from the control condition after 200 m before the on-ramp location (see Fig. 6). The results of mean speed and headway values provide an additional explanation for the difference in lane position.

5.1.3. Mean distance headway: Lead vehicle

Pairwise comparisons for the mean distance headways to the lead vehicle were conducted before the merge zone. The headway values to the lead vehicle indicated that there are significantly larger headways over all zones in the AGM signalization condition when drivers approach the on-ramp. Mean headways over the travel distance of 450 m increased significantly until the on-ramp, which was not the case in the control scenario ($F_{(2,123)} = 18.28$, $p < 0.001$). A significant headway difference of 43 m was measured between AGM signalization and control condition ($F(2,126) = 18.52$, $p < 0.001$) at 200 m before the on-ramp when the merging vehicle became visible. Despite much higher approaching speeds for the 100 km/h highway where the AGM with VSL 80 km/h was implemented, no shorter distance headways were found as compared to the 80 km/h highway control condition. This indicates that distance headways were actively adjusted before 200 m due to the AGM signalization. Fig. 7 shows the distance headway values per traveled zonal distance until the merge location for all three conditions. A color segmentation was applied to visualize the strength of the headway decrease to the lead vehicle.

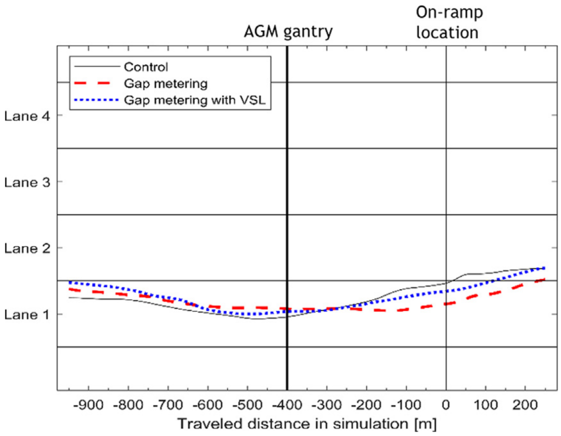
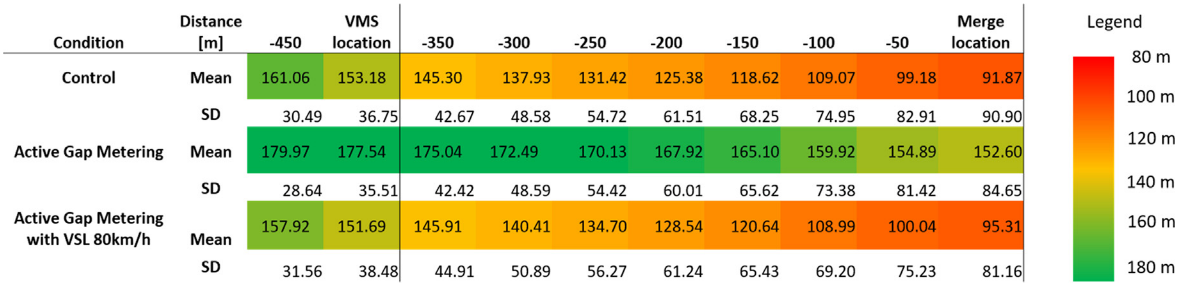


Fig. 6. Drivers' mean lateral lane position in all conditions.



Condition	Distance [m]	-450	VMS location	-350	-300	-250	-200	-150	-100	-50	Merge location
Control	Mean	161.06	153.18	145.30	137.93	131.42	125.38	118.62	109.07	99.18	91.87
	SD	30.49	36.75	42.67	48.58	54.72	61.51	68.25	74.95	82.91	90.90
Active Gap Metering	Mean	179.97	177.54	175.04	172.49	170.13	167.92	165.10	159.92	154.89	152.60
	SD	28.64	35.51	42.42	48.59	54.42	60.01	65.62	73.38	81.42	84.65
Active Gap Metering with VSL 80km/h	Mean	157.92	151.69	145.91	140.41	134.70	128.54	120.64	108.99	100.04	95.31
	SD	31.56	38.48	44.91	50.89	56.27	61.24	65.43	69.20	75.23	81.16

Fig. 7. Drivers' distance headway to the lead vehicle.

5.1.4. Mean distance headway: on-ramp vehicle

Pairwise comparisons of the mean headway values to the merging vehicle from the on-ramp were conducted to investigate the effect of each AGM scenario on the available spacing that facilitates safer responses to merging maneuvers of on-ramp vehicles. The results indicate that there were significantly larger headways in the measurement zones with AGM signalization as compared to the control condition. The merging vehicle became visible at 200 m before the on-ramp location. The AGM treatment helped drivers to significantly increase the headway by 13 m to the on-ramp vehicle until the merge location ($F_{(2,\ 124)} = 12.06$, $p < 0.001$). At the merge location itself, a headway difference of 44 m was measured between the AGM and control condition for the same highway speeds ($F_{(2,131)} = 27.93$, $p < 0.001$). This contrast is visualized in color segmentations for the traveled zonal distance displayed in Fig. 8. This increase in headway corresponds to the distance between two chevron markings. As a result, the safety distance to the merging vehicle was significantly increased. In total, a distance headway of 74 m to the merging vehicle on the tapered on-ramp was achieved, whereas far shorter headways were measured in the control condition (see Fig. 8). When taking a look at the AGM with VSL 80 km/h condition for the higher speed highway, it becomes evident that the AGM with VSL signalization results in larger headway values starting at the merge location itself as compared to the 80 km/h highway control scenario. However, post hoc tests revealed that the headway increase of 7.7 m at the merge location was insignificant.

5.1.5. Minimum time-to-collision

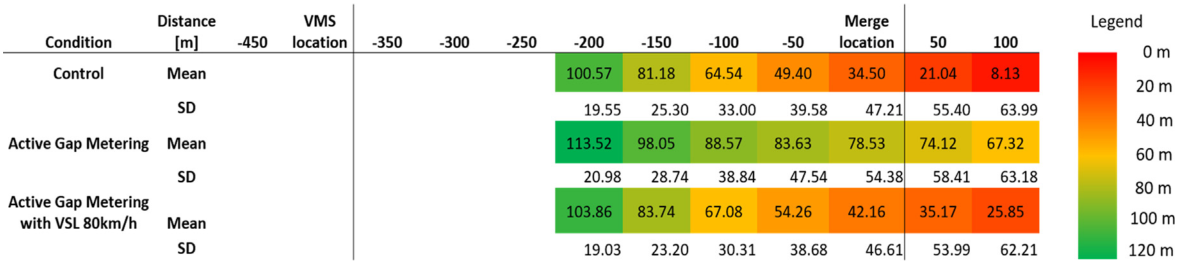
Literature suggests that at a headway of around 6 s, drivers are able to choose their traveling speed independent of the vehicle ahead. Therefore, TTC values larger than 6 s are generally safe (Vogel, 2003). For this analysis, $\mathrm{TTC}_{\min}$ values of less than 5 s towards the lead vehicle and the merging vehicle were investigated per driving condition. The descriptive results are presented in Table 4, whereas Table 5 shows the univariate tests of between-subject effects that were conducted with Bonferroni adjustments at a significance level of $\alpha = 0.05$. Table 4 shows that the shortest mean $\mathrm{TTC}_{\min}$ value to the lead vehicle has been found in the control condition (0.521 s), whereas a somewhat similar mean $\mathrm{TTC}_{\min}$ to the lead vehicle has been found for AGM (0.612 s) and AGM with VSL 80 km/h (0.604 s). The mean $\mathrm{TTC}_{\min}$ values towards the merging vehicles from the on-ramp showed that the lowest $\mathrm{TTC}_{\min}$ values were measured in the control condition (0.896 s). In contrast, mean $\mathrm{TTC}_{\min}$ of 1.537 s to the merging on-ramp vehicle were found for the AGM alone, and even 2.053 s to the merging on-ramp vehicle were found for AGM with 80 km/h. The pairwise comparisons revealed a significant increase of 1.45 s in $\mathrm{TTC}_{\min}$ when the AGM with VSL 80 km/h condition was implemented as compared to an untreated 80 km/h highway ($p = 0.033$). The AGM and AGM with VSL 80 km/h condition were not significantly different from each other, which indicates that both strategies have a similar impact on improved $\mathrm{TTC}_{\min}$ values to the merging on-ramp vehicle.

6. Discussion and recommendation

In this study, a new AGM signalization was proposed and tested on highway sections with an on-ramp vehicle acceleration speed of 80 km/h. AGM strategies for highway speeds of 80 km/h and 100 km/h before the on-ramp sections were analyzed to examine the effect on distance headways to merging vehicles.

6.1. Distance headway

We can confirm the hypothesis that the distance headway to the lead vehicle increased significantly until the merge section if AGM signalization was present on the same 80 km/h highway. When the AGM with VSL 80 km/h was implemented on the 100 km/h speed highway, a significant speed reduction was gained when the VMS gantry was within the legible distance. The differences in initial mean speeds became insignificant once the drivers were located in the designated pre-merge area in all three scenarios. The increased headway values achieved by the AGM signalization provide evidence that drivers better adjusted their headways to the lead vehicle to cooperate with merging on-ramp vehicles as compared to the highway scenario without treatment. It might also be argued that the AGM signalization designed for outer lane mainstream drivers can



Condition	Distance [m]	-450	VMS location	-350	-300	-250	-200	-150	-100	-50	Merge location	50	100
Control	Mean						100.57	81.18	64.54	49.40	34.50	21.04	8.13
	SD						19.55	25.30	33.00	39.58	47.21	55.40	63.99
Active Gap Metering	Mean						113.52	98.05	88.57	83.63	78.53	74.12	67.32
	SD						20.98	28.74	38.84	47.54	54.38	58.41	63.18
Active Gap Metering with VSL 80km/h	Mean						103.86	83.74	67.08	54.26	42.16	35.17	25.85
	SD						19.03	23.20	30.31	38.68	46.61	53.99	62.21

Fig. 8. Drivers' distance headway to merging vehicle.

Table 4
Descriptive statistics for $TTC_{min} < 5$ s.

Condition	Conflict vehicle	Mean TTC_{min} [seconds]	Standard Deviation	N
Control	Lead vehicle	0.5205	1.0574	30
	Merging vehicle	0.8958	1.4441	38
Active Gap metering	Lead vehicle	0.6121	1.1542	27
	Merging vehicle	1.5365	1.6916	28
Active gap metering with VSL80 km/h	Lead vehicle	0.6036	1.2091	16
	Merging vehicle	2.0529	2.0759	28

Table 5
Univariate test of between-subject effects for TTC_{min} to merge vehicle.

Source	Type III Sum of Squares	Df	Mean Square	F	p-value	$\eta\rho^2$
Corrected Model	52.467a	5	10.493	4.696	<0.001[**]	0.127
Intercept	167.848	1	167.848	75.110	<0.001[**]	0.318
Condition	52.467	5	10.493	4.696	<0.001[**]	0.127
Error	359.786	161	2.235			
Total	598.473	167				
Corrected Total	412.253	166				

[**] Significant at $\alpha < 0.001$.

be potentially beneficial for on-ramp sections that are occasionally characterized by aggressive merging maneuvers, such as described in a French study (Marczak et al., 2013).

When looking at the results of the proposed AGM signalization to influence the distance headways to the merging vehicle at critical on-ramp sections, it becomes clear that the AGM signalization was very effective. The distance headway to the merging vehicle was significantly increased by 44 m as compared to the normal headway choice on a non-treated highway. It is no coincidence that the AGM signalization with the chevron markings primed drivers to keep this gap distance since the advised two chevrons correspond to approximately 45 m (AWV, 2019). The distance headway depends on the driver's comfort regarding vehicle speeds at 80 km/h and is typically around 44 m, which has also been confirmed in on-road studies testing radar-based ACC (Stein, Mano, & Shashua, 2003). The increase in distance headway of 43 m to the lead vehicle contributed to the driver's ability to safely accommodate merging vehicles from on-ramps. In the literature, a headway of two seconds is recommended for safely driving behind a lead vehicle. However, unexpected emergency stops when driving at 80 km/h require a total braking time of above five seconds, which is equivalent to a total braking distance of 70 m (SWOV, 2012). Interestingly, the zonal mean headway values to the merging vehicle that have been measured during the entire length of the 150 m tapered on-ramp section are meeting this headway distance (~74 m). This shows that drivers are not only alerted to increase the headway gap to accommodate an on-ramp vehicle, but they are also more aware of the induced risk of rear-end collisions before on-ramp sections, which was reflected by the headway values.

6.2. Minimum TTC

The last hypothesis of this paper stated that critical TTC_{min} values to the merging vehicle could be eliminated if AGM signalization is present. In the literature, it was referred to the fact that when a vehicle merges into the headway, the concurrent headway is reduced by half (Marczak et al., 2013). Due to the implemented AGM signalization, drivers were able to consistently increase their distance to the lead vehicle before the on-ramp section to proactively compensate for the expected halving of the headway when an on-ramp vehicle started to merge into the traffic stream. Very low mean TTC_{min} values of 0.5 s were found in the control condition of the 80 km/h highway stretch, which indicates that implementing the same speed on highway and on-ramp is not sufficient to eliminate merging conflicts. By implementing AGM before the merging section, the mean TTC_{min} to the on-ramp vehicle was actively increased to 1.54 s. According to the literature, a TTC_{min} of 1.5 s or less is used as a threshold for unsafe situations, whereas TTC values between 1.5 and 2 s are considered low risk (Dijkstra et al., 2010; Morando et al., 2018; Räma & Kulmala, 2000). More than 2 s to the merging on-ramp vehicle was achieved for the AGM with VSL 80 km/h scenario. Despite the higher approaching speeds of drivers on the 100 km/h highway, the combined AGM with VSL 80 km/h resulted in safe TTC_{min} values of 2 s to the merging on-ramp vehicle. This increase in mean TTC_{min} can be considered valuable for conflict and crash prevention at highway merge target lanes and confirms the effectiveness of the AGM signalization in increasing drivers' alertness and headways to merging on-ramp vehicles when applied on the outer driving lane. The findings confirm that Active Gap Metering with VSL 80 km/h is similarly effective as the Active Gap Metering being installed at a highway section with a standard speed limit of 80 km/h, which suggests that AGM can be perfectly combined with another active traffic management strategy such as VSL as it was suggested by Soriguera et al. (2013). Both conditions are significantly effective in improving headways and TTC_{min} compared to an untreated 80 km/h highway.

So far, researchers and practitioners commonly promote the two-second rule as a time headway heuristic. Although this rule is generally valid, it comes with many limitations since drivers are often not able to translate a time headway count into actual safe driving behaviors. Particularly, before locations with changing traffic conditions such as at highway merge sections, drivers require additional spatial-visual references to safely adjust their distance to the lead and merging vehicles, as was shown in our experiments. This research proposed an innovative and beneficial intelligent transportation system application based on AGM tested alone and in combination with VSL depending on the highway environment. The signalized headway distance of two chevron markings was successfully achieved towards the new lead vehicle that merged into the lane and the TTC_{min}, resulted in low-risk values of 1.5–2 s at its most critical state, indicating an improvement of 1 – 1.5 s as compared to no AGM treatment. The implementation of an AGM signalization is, therefore, recommended at locations with frequent vehicle conflicts, where drivers require additional visual guidance for a safe headway choice.

7. Conclusion and future research

The AGM provides visual guidance through the use of VMS and chevron markings to help drivers on the right lane traffic stream to adjust their headways to the lead vehicle before on-ramp merge areas. It can be summarized that the AGM actively addressed drivers to slow down and adjust the distance headway to safely accommodate merging vehicles from the on-ramp. It was also shown that the distance headways to the lead vehicle were gradually increased over the zones, which resulted in larger distance headways and larger mean TTC_{min} values to the merging on-ramp vehicle if the AGM signalization was in place. The AGM signalization can, therefore, be considered by road authorities to treat highway merging sections with a history of merge conflicts due to fluctuating traffic densities and competition for space due to tapered on-ramp geometries. The dynamic component of the AGM signalization provides several real-time solutions to manage dynamic and controlled gap spacing for highway merge sections. Future studies should further focus on these applications.

It should be mentioned that the composition of international drivers in Qatar is unique. Our sample was a good representation of the average driver in an internationally mixed driving population such as in Qatar, which makes it possible to generalize the results to other countries with a heterogeneous population that deal with similar merging conflicts. Follow-up studies with larger sample sizes are required to further corroborate the findings of this study. The results in car-following behavior measured in the driving simulator are generally reflected by studies using traffic field data. However, there is a risk that specific variables in isolation are deviating from the field (Papadimitriou & Choudhury, 2017). Therefore, it is recommended to conduct on the road test trials with AGM implemented in reality. Another limitation might be that only one headway (distance between two chevrons) was signalized in this study. Follow-up research could test how drivers respond to different combinations of chevron flashing on the VMS that is adapted based on the changes in traffic density and driving speeds. Moreover, future research is recommended to investigate drivers' responses if the same AGM message is displayed as a full in-car display system. This could include the integration of augmented signs and markings displayed on the windscreen to communicate the need to adjust the gap space to the driver or occupants of the car.

Generally, the tested AGM signalization is a promising approach to provide warning and visual guidance for safe headway choices at critical on-ramp sections with merging traffic. The AGM strategies represent an effective and easy alternative to time-based headway heuristics because it nudges drivers into performing desirable safety behaviors. This is particularly important in multicultural driving communities where headway heuristics are often incorrectly performed due to cultural, educational, and individual factors.

7.1. Design implications in the field of ITS

The ITS are deployed to sense, communicate, and control the road network with the final goal to increase traffic safety and efficiency. This includes the design and implementation of active gap metering signalization that takes human limitations into account and provides better services to drivers.

The driving speeds at particular hours of the day should be monitored to take into account the impact of increased traffic during rush hours on vehicle headways. If driving speeds fall under a certain threshold, the AGM signalization can be modified, displaying only one flashing chevron on the VMS. Therefore, the signalized placeholder of one chevron marker in the imminent headway can actively suggest alternate merging at lower speeds under high traffic densities, which might also be beneficial in case of highway lane closures. Further application opportunities for AGM signalization are available for highway merging sections with faster mainstream speeds. For instance, AGM in combination with VSL should be applied for highways with speed limits of 100 km/h and above to control for the initial differences in driver approaching speeds to merge sections with tapered on-ramp designs such as tested in this study. There is also the potential to apply AGM signalization when equal priority highways merge together.

The VMS is a highly flexible computer-based panel, which can change its display in real-time when the traffic conditions on the road change (Castro & Horberry, 2004). This provides road authorities with the opportunity to change the displayed number of flashing chevrons of the AGM signalization (e.g., three flashing chevrons to signalize a larger headway distance) in case of on-ramp trucks or long vehicle types merging on the right highway lane. The VMS design of the proposed AGM signalization has been specifically designed for this research addressing passenger cars. Therefore, the recruited drivers in this study have been questioned about their evaluation of the design attributes of this AGM signalization. The questionnaire revealed that 92.2% of the drivers agreed that the red flashing chevron on the VMS attracted their attention. Almost 80% of drivers indicated that the content of the sign is very well arranged in terms of visibility and readability. Also, 81.3% of the drivers indicate that the implications of this warning are very clear, and they know that they have to maintain a distance to the vehicle in front. Nevertheless, only 64.1% of the drivers responded that the sign is clearly referring to a merging section ahead, which might be attributed to the fact that drivers don't have sufficient time to comprehend all details displayed on the VMS. Besides, 75% of the drivers agreed that the chevrons markings clearly suggest keeping a distance. Only 26.6% of drivers responded that the sign is very complex to understand, which may be due to the fact that drivers have no experience with such a traffic management system yet. Many VMS panels are recently installed in Doha City (Qatar), and it is expected that in the near future, this network of VMS panels will be effectively used to implement different adaptive traffic management strategies. The biggest challenge for the future of ITS will be the mix of automated, connected, and conventional vehicles on the road. ITS has to take into account the limitations of the human drivers who will remain on the road.

CRediT authorship contribution statement

Nora Reinolsmann: Conceptualization, Software, Methodology, Formal analysis, Investigation, Writing - original draft. **Wael Alhajyaseen:** Funding acquisition, Supervision, Project administration, Conceptualization, Validation, Resources, Writing - review & editing. **Tom Brijs:** Conceptualization, Validation, Writing - review & editing. **Ali Pirdavani:** Methodology, Writing - review & editing. **Qinaat Hussain:** Investigation, Writing - review & editing. **Kris Brijs:** Methodology, Validation, Writing - review & editing.

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