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Delay or travel time information? The impact of advanced traveler information systems on drivers' behavior before freeway work zones

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ABSTRACT

Peak travel times contribute to congestion formation at freeway work zones. Advanced Traveler Information Systems (ATIS) can inform drivers in real-time about the delays and travel times en-route and can provide information about an alternative route to a destination. Different ATIS display strategies are available; however, road authorities lack insights into how time display methods and sign characteristics influence the driving behavior (decelerations, lateral position), the drivers' attention allocation ability and the subsequent route choice before the freeway diversion. A driving simulator study was conducted with 80 drivers in the State of Qatar to investigate drivers' behavior and voluntary route choices when encountering total travel time (default setting) or delay time updates for two freeway routes on Variable Message Signs (VMS) and Graphical Route Information Panels (GRIP). The GRIPs are a graphical alternative to conventional VMS that can provide drivers with a visual map of the most direct route or an alternative less congested route to a destination using different color schemes. The time difference ratio between the two routes was kept constant to compare the effectiveness of the information designs and investigate the drivers' attention towards the signs with an eye-tracker. The results showed that the display of zero delays for a detour did influence 74–83% of the drivers to take the alternative route when being displayed on a VMS and a GRIP with free flow attribute framing. When displaying equal total travel times, the GRIP did influence 25% more drivers to follow the alternative route than the VMS. Generally, displaying zero delays for the alternative route resulted in an efficient attention allocation to the first ATIS location and fewer mean decelerations before the repeated ATIS location nearing the diversion. Road authorities are advised to activate the display of delay times to support efficient route choices among freeway drivers.

1. Introduction

Road works are essential to maintain the quality of freeway infrastructure. However, road construction and maintenance projects

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have a significant effect on the operational performance of freeways leading to an increase in congestion and delay during the construction period. At peak travel hours, these freeway work zones are turning into bottlenecks since an increased number of vehicles need to pass through the work zone at lower operational speeds. This strongly affects driving comfort and increases stress. From a driver's perspective, a freeway work zone has the potential to add long delays to the trip due to slow speeds and increased interactions with other vehicles. An important aspect of perceptions about congestion is the physiological arousal accompanying negative evaluations of other drivers who constrain the free flow movement. Several studies have found that drivers report more stress and time pressure on days when levels of congestion are high on a particular route (Hennessy & Wiesenthal, 1999; Higgins, Sweet, & Kanaroglou, 2018). An Advanced Traveler Information System (ATIS) can, therefore, play an important role in informing and warning drivers for congested conditions during peak travel hours while presenting a time-wise alternative with free-flow conditions to reach the intended destination. Road authorities aim to influence the navigational decisions of drivers to improve the overall traffic conditions on the freeways. The ATIS is a promising technology that can be activated during specific days of the week or times of the day to inform drivers about peak congestion at freeway work zones. However, the implementation of such a system requires careful design and implementation considerations to safely attract the driver's attention, to present an understandable message and to influence driver's route choice efficiently. A comprehensive literature review has been conducted to learn from past research and to identify the most promising ATIS designs that can optimally address driver behavior and motivate route choices at strategic freeway interchanges. For instance, ATIS technologies such as Variable Message Signs (VMS) or Graphical Route Information Panels (GRIP) can be implemented to display dynamic travel information at strategic freeway network junctions. These signs provide drivers with real-time updates about travel times but can also be used to display delay due to work zone related congestion on the main route. Since the contents displayed with ATIS cannot be personalized, it essential to evaluate new ATIS design formats before freeway junctions prior to their implementation. Drivers do not often sufficiently process a displayed change in travel information on VMS to respond in an adequate manner (Martens & Fox, 2007). Therefore, drivers attention and response to dynamic ATIS configurations for time wise equal routes with updated traffic conditions is investigated at a freeway interchange link.

1.1. Driver route choice behavior

Information availability about increased travel times due to road works and crashes can lead to travel adaptations already before the trip (e.g., departure time choices) but also en-route when dynamic route choices must be made. Travelers are actively looking for information if high variability or uncertainty exists about the travel time (Peirce & Lappin, 2003). Khattak, Yim, and Prokopy (2003) found that about 30% of drivers who participated in a survey do frequently change their travel behavior in response to information, and 96% of the drivers changed their trips 'occasionally'. A later study by Khattak, Pan, Williams, Rouphail, and Fan (2008) further added that the likelihood of route changes among drivers increased from 22% to nearly 65% when travel information could be consulted daily. Ran, Barrett, and Johnson (2004) conducted a survey among 217 drivers in Wisconsin and found that almost 67% of the drivers would take a detour if the travel time on the freeway was at least 15 min longer than normal. Furthermore, the percentage of drivers who will follow the alternative route increased to 76% if the VMS displays a traffic delay due to road construction. Those drivers who would not change the travel route reported high uncertainty of whether the alternative route would be faster or not (Ran et al., 2004). Ben-Elia and Avineri (2015) highlighted that drivers' past experiences and familiarity with the road network could influence VMS compliance. For example, drivers may choose to ignore the provided travel information due to their familiarity with the road network and situational factors such as time of the day, trip purpose, evaluation of traffic conditions, etc. (Moghaddam, Jeihani, Peeta, & Banerjee, 2019; Yan & Wu, 2014). The driving simulation study by Moghaddam et al. (2019) investigated the determinants of drivers' route choice behavior on a freeway network (including a toll road) based on VMS displaying travel time information and compared the results to a stated preference (SP) survey. Based on the results from 65 subjects the study concluded that the trip purpose (work/ leisure), perceived travel time reliability, and income are determining factors of the route choice and that responses from the survey do not always reflect the route choice under simulated conditions. This study also adds to the discussion that the display of a travel time range is not necessarily perceived more reliable than displaying exact travel time information, because subjects tend to consider the worst-case maximum travel time in the provided range (Moghaddam et al., 2019). This might indicate that drivers consider the anticipated delay to estimate travel time reliability, which requires further research elaboration.

Ringhand and Vollrath (2018) investigated drivers' compliance with urban route recommendations based on system-optimal traffic management through conducting an online survey with 144 subjects and a driving simulator experiment with 48 participants. The online survey showed that travel time recommendations are evaluated as less important in the absence of time pressure, although a main effect was not found. Time pressure was not included in the driving simulator experiment, even though the authors admitted that driving itself can be perceived as a loss of time that is not being spent on other productive tasks (Ringhand & Vollrath, 2018). Perceived time pressure was identified as a significant variable in a previous driving simulator study with 64 drivers (Ringhand & Vollrath, 2017). The results indicated that one-third of the drivers took an alternative route with longer travel times on an urban road network to avoid red traffic lights (Ringhand & Vollrath, 2017). A follow-up driving simulator study by Ringhand and Vollrath (2019) was conducted on urban roads and built upon earlier insights (e.g., Ringhand & Vollrath, 2018) that highlighting the alternative route positively through green color increases the compliance of drivers. It should be noted that the travel information was simply displayed on the simulator screen without considering the design requirements for on-road travel information signs. The results of Ringhand and Vollrath (2019)'s simulator study showed that positively framing the personal gain for the alternative route was more effective than highlighting the loss on the main route. Furthermore, the authors stated that compliance with alternative route advice is influenced by the travel time difference. The study of Li et al. (2014) reinforces that VMS/GRIPs should only display an alternative route advice if the detour path has advantages over the other route to counteract traffic flow fluctuation and optimize the network performance. The authors investigated cooperative driver responses to detour information displayed on color-coded GRIPs without travel time information. The results of their simulation model showed that the network condition could be improved by 26.3% due to the VMS/GRIP. The terminology of VMS and GRIP was not distinguished. Therefore, it remains unclear which impact the design configurations of VMS and GRIP would have on the real-time driver responses before the link diversion.

It can be summarized that several studies that have compared the intended route choices from stated preference questionnaires with observations from the field have shown inconsistencies. A substantial percentage of drivers stated that they would divert from their route given reliable information about the expected delay. However, the results from the field have shown that a much larger percentage of drivers did not divert, which might be attributed to unconvincing, incredible, or unattractive alternative route messages provided by on-road ATIS (e.g., Horowitz, Weisser, & Notbohm, 2003; Knoop, Hoogendoorn, & Zuylen, 2010; Moghaddam et al., 2019; Wang, Khattak, & Fan, 2009; Wardman, Bonsall, & Shires, 1996).

1.2. Design configurations of advanced traveler information systems

Two types of ATIS are currently in use around the world: Variable Message Signs (VMS) and Graphical Route Information Panels (GRIP). The most common system for road work warnings is the text-and numerical based VMS that can be accompanied by warning pictograms. The VMS can display different types of information such as travel time, average speed, distance, and information about delays and incidents on a roadway. Robinson, Lerner, Singer, Baragan, Kulbicki, and Kline (2017) published a technical report that discussed optimal display options for advanced travel time information. The report highlights that time indications on VMS should be displayed in minutes and that drivers are more willing to divert when also given specific details on the alternative route, such as travel times or open-ended time estimations (Robinson et al., 2017). However, the report did not specify the distinct effects on route diversions if either travel time or delay times are displayed on the VMS. Furthermore, messages should be concise and to the point to improve message legibility and should be limited to no more than three lines of text or five to six information units for freeway speeds of 120 km/h (Arbaiza & Lucas-Alba, 2012). Displaying descriptive text such as ‘Mayor delay’ as proposed by Robinson et al. (2017) could be omitted from the VMS if the delay time itself is shown for all available routes. Therefore, lengthy messages consisting of more than six words can be avoided since drivers need to read and process the information within few seconds to make an informed decision (Arbaiza & Lucas-Alba, 2012; Robinson et al., 2017). Zhou and Wu (2006) developed a model to determine the probability of diversion in the presence of VMS information. The authors found that drivers are paying attention to the dynamic messages on the VMS and evaluate the accuracy of information as one of the most important factors influencing drivers’ route choice behavior. The authors recommend that providing clear information (i.e., when and where to divert) is crucial to support drivers’ diversion decisions.

The GRIPs are a graphical alternative to conventional VMS that can provide drivers with a visual map of the most direct route or an alternative less congested route to a destination (Shalloe et al., 2014; Sharples, Shalloe, Burnett, & Crundall, 2016). The GRIPs with different designs have already been implemented in several countries around the world to improve drivers’ orientation and comprehension of traffic information for a particular road network (Gan, Saha, Haleem, Alluri, & McCarthy, 2012). The GRIPs use color representations, such as red, orange, and green, to display locations of congestion, slow traffic, and free travel conditions and support drivers to evaluate the traffic conditions on an alternative roadway (Robinson et al., 2017). These GRIPs have the advantage of presenting more detailed travel information while displaying less text on one panel. Scientific research has addressed the influence of these panel types on the information reading and processing ability of participants, given that GRIPs are still less common on freeways than conventional VMS infrastructure. For instance, one- and two-color combinations and map shapes (abstract vs. naturalistic, triangle vs. tetragon network) displayed on the GRIP were further investigated by a computer-based comprehension study (Reinolsmann, Alhajyaseen, Brijs, Ross, et al., 2019) and a driving simulation study (Lai, 2012). An abstract map shape was recommended when displaying two traffic state colors (Reinolsmann, Alhajyaseen, Brijs, Ross, et al., 2019), and a triangle network shape performed better than a tetragon shape (Lai, 2012). However, no direct comparison has been made between the impact of GRIP and VMS on driving behavior.

An interactive computer study and stated preference survey was conducted among drivers in Qatar to understand which ATIS design and display factors influence drivers’ route choices to a specified destination (Reinolsmann et al., 2020). The participants’ route choices after limited exposure to different display strategies on text-based VMS and network-based GRIP were measured in the computer task and revealed more route diversions for the GRIP than the VMS. Besides, the results from the stated preference survey showed that respondents preferred delay times on the GRIP but total travel times on VMS (Reinolsmann et al., 2020). These results have not been confirmed yet under (simulated) driving conditions. Thus, the distinctive influence of GRIP and VMS on drivers’ attention, behavior and route choices remains speculative. For instance, Moghaddam et al. (2019) used a driving simulator to investigate the impact of travel time reliability, which is a concept that relates to the expected variabilities in travel time for the same trip on different days and times. Route choices made in the simulator were compared with route choices indicated in a stated preference survey. Interestingly, the authors found inconsistencies in the stated and revealed route choices, with 50% of drivers stating that they would take a certain route while only 36% of the drivers were effectively taking this route in the simulator. These findings highlight the necessity to replicate the driving context in which route choices are made. Driving simulations make it possible to study the effect of ATIS considering the increased cognitive demands associated with the complexity of driving and decision-making under dynamic conditions. Research investigating driving behavior has started to include eye-trackers in the methodology to measure drivers’ visual attention through eye fixations, which are relatively stable moments when the drivers’ eyes focus on an area in the driving environment (Robbins, Allen, & Chapman, 2019). These eye fixations most often reflect the fact that the brain is processing the fixated information. The information intake is primarily dependent on the available focus of attention, which can be measured through overt eye movements (Crundall & Underwood in Porter, 2011). Parameters of visual processing are, for instance, the number of eye fixations as well as the average fixation duration on a travel information sign. Longer eye fixations indicate a longer interpretation time of the displayed information, which can potentially distract the driver from the driving task (Porter, 2011).

1.3. ATIS implementation on the freeway

In research, driving simulators are increasingly applied to investigate drivers' behavior during route choice situations and the consequences for driver safety. For instance, Yan and Wu (2014) analyzed how the VMS location and display format of guidance information (text only or graphics) before a simulated urban intersection (speed limit of 80 km/h) influenced drivers' route choices, speed adjustments, and lane change behavior. The study findings of 52 drivers demonstrated that the VMS location of up to 200 m before the intersection and a graphical route display has a significant impact on driving behavior. The average driver started to adjust his/her driving speed and path already 70 m before the VMS location (Yan & Wu, 2014). These findings are, however, limited by the simulated urban road setting with lower driving speeds than on freeways. A driving simulator was also used to investigate if safe exiting maneuvers could be achieved at various distances of the VMS from the freeway off-ramp (Oh, Kim, Lee, Choi, & Joo, 2012). The authors predicted the probability of a successful exiting maneuver based on the VMS location, driving behavior, and drivers' demographics. Based on the 85th percentile success rate, they found that a male driver having a license type for large vehicles and freeway driving experience requires a spacing of 1.91 km between the VMS and the ramp to conduct a safe exit maneuver. Results from a driving simulator study conducted by Robinson et al. (2017) indicate that drivers prefer travel time information on VMS to be placed approximately 0.5 miles (800 m) before the freeway exit ramp, which corresponds with the guidelines for spacing distances of static direction signs on freeways. The spacing between VMS infrastructure is usually defined as 400 m to 1000 m and has to be integrated carefully into the existing road infrastructure (Margison, 2008). Moreover, Robinson et al. (2017) highlighted that drivers evaluated VMS displays of travel times to be most valuable when placed near the recommended freeway exit. It was mentioned that drivers require travel time information at a vital decision point and would prefer to see it while approaching the freeway ramp. Sharples et al. (2016) conducted a driving simulator study to investigate the impact of different textual VMS incident warnings with additional advice or instructions on driving behavior. The results showed that firstly, drivers were more likely to slow down if the information was repeated. Secondly, the inclusion of information about the length of delay resulted in more route adjustments. Thirdly, reporting the specific nature or cause of an incident encourages drivers to trust the information more as compared to a general reference to 'congestion' (Sharples et al., 2016). The reviewed studies suggest that VMS warning and guidance information should be provided at a sufficient distance from a freeway off-ramp and be repeated near the recommended freeway exit. Still, the literature concerning the implementation and placement of GRIPs on freeways remains scarce and it is unclear whether the implementation recommendations for VMS are transferable for GRIPs displaying warning and guidance information at freeway locations characterized with international drivers and divers driving behaviors.

1.4. Travel time and delay sensitivity

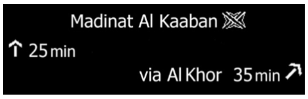
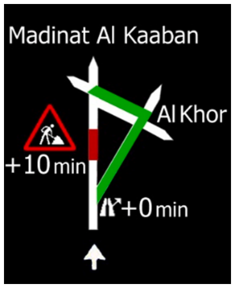
The exact impact of ATIS depends on drivers' behavioral and cognitive responses to the provided information (Ben-Elia & Avineri, 2015). However, in dynamic driving situations, simple choice heuristics often outweigh rational decision making (e.g., Simon, 1972) to solve problems in an acceptable quick way (Ben-Elia & Shiftan, 2010). More specifically, drivers' interpretation of the displayed travel information is influenced by an evaluation of the simplest and shortest paths in terms of distance, time, and effort (Montesinos, Ortelli, Kazagli, Bellocchi, & Geroliminis, 2017). The evaluation of path simplicity can be influenced by the number of geometrical turns on the network (Lai, 2012; Viana, Strano, Bordin, & Barthelemy, 2013) as well as the driving demands and traffic conditions associated with a route (Montesinos et al., 2017). The study of Li, Lin, He, and Jiang (2016) investigated traveler's route choices on a network with recurrent congestion using a network equilibrium model. It was highlighted that the link-specific perceptions should be addressed and that increasing the accuracy of drivers' perceived travel times through poorly designed VMS can lead to an increase of network-wide system delay. It was concluded that real-time traffic information should, therefore, be managed dynamically and link-specifically to mitigate congestion. Limitations of this study are that no definition of a poor VMS design was provided and that the design impact on driver's behavior was not specified.

Reinolsmann et al. (2020) investigated in a computer-based experiment the sensitivity to delay and travel time increases on freeways among drivers in Qatar when traveling on a free weekend or workday. Total travel times, delay times, and regular travel time plus delay were displayed in combination with warning pictograms showing the reason for the delay (e.g., crash, work zone, congestion). The results indicated that the drivers were willing to divert from their original route if taking the alternative would be at least 10 min faster or if the delay on the original route would be at least 10–15 min. On free days, a distinct group of drivers (31.6% of the 114 surveyed drivers) would take the alternative route already when the total travel times are equal to the originally intended route and if traffic hinders could be avoided. Furthermore, crash warnings did generally increase the probability of diverting to the alternative route, which was also supported by the results of Ben-Elia and Avineri (2015), who stated that non-recurring incidents such as crashes are considered as being a greater source of uncertainty. Road work-related warnings benefited most from the displayed delay time strategy for the two available routes since the diversion rates were clearly increased as compared to the other time display methods (Reinolsmann et al., 2020). Given that the route choices were not made under realistic driving demands, it was recommended to replicate a work zone congestion incident in a driving simulator to investigate the impact of VMS and GRIP displaying total travel time and delays on drivers' voluntary route choices and driving responses. Moreover, the specific characteristics of the driving population in Qatar with the many cultural and educational backgrounds and driving behaviors should be replicated to identify the most effective information design and ATIS message strategy that provides safe advice for all drivers on the freeway (Timmermans, Alhajyaseen, Reinolsmann, Nakamura, & Suzuki, 2019, Timmermans, Alhajyaseen, Ross, & Nakamura, 2020). Several driving simulator studies were conducted in the state of Qatar. Hussain, Alhajyaseen, Brijs, et al. (2019) found higher speed variations among drivers in Qatar when the speedometer was not visible, indicating that drivers tend to underestimate their driving speeds in case of complex situations when they cannot attend to the speedometer. Reinolsmann, Alhajyaseen, Brijs, Pirdavani, et al. (2019) found that harsh decelerations and abrupt lane changes in response to lane merging vehicles from rural freeway on-ramps in Qatar increase the crash- and congestion risk. Also, the analysis of crash data from Qatar from the past decade revealed that reckless driving and overspeeding were among the main behavioral contributing factors to severe road traffic crashes (Timmermans, Alhajyaseen, Al Mamun, et al., 2019).

2. Objectives

The VMS and GRIP can be activated before strategic interchange locations (e.g., freeway divergence) to provide drivers with real-time travel information for the original route and an alternative route in case roadworks cause congestion during peak travel hours. In this paper, we aim to investigate whether message-related aspects (i.e., delay or travel times) and the way they are presented (i.e., GRIP vs. VMS) influence drivers' route choices. Whereas total travel time displays are simply informing drivers about the expected arrival times, displaying traffic delays might be better suited to influence drivers' route choices because information about the expected level of traffic is provided. In addition to that, drivers' attention to the ATIS (measured with an eye-tracker) and driving behavior (in the simulator) will be studied to better understand the drivers' interaction with these messages on the road. More specifically, it will be investigated whether drivers can safely process the GRIP and VMS based travel information at first and repeated exposure while driving. Research shows that road users usually fail to attend to the information aimed at guiding, controlling, or regulating traffic (Costa et al., 2014). A graphical interface (color-coded GRIP) may improve or worsen the driver's attention allocation and

Table 1
An overview of the test conditions.

N	Phase	Description	Message on VMS	Message on GRIP
control	No incident	Regular travel time to Madinat Al Kaaban without road works		
1	Warning phase 1 a) travel time	Road works warning: Congestion on the original route. The free flow travel time for the alternative route via Al Khor is the same as on the original route.		
2	Warning phase 1b) delay time	10 min delay on the original route because of road works. Zero delays on the free flow alternative route via Al Khor		
3	Warning phase 2 Increased delay on both routes	Delay increased to 15 min on the original route with road works whereas 'rerouting' drivers did increase the traffic volume on the alternative route causing 5 min delay.		

consequential deceleration and lateral position adjustments since more information units are displayed compared to a conventional text-based VMS. These insights can help road authorities select the most effective and acceptable ATIS strategies for dynamic traffic management on freeways.

A preselection of best practice ATIS strategies has been done in a computer-based comprehension study (Reinolsmann et al., 2020). The optimal designs for work zone warning and rerouting purposes have been selected for further testing in a driving simulator replicating the freeway environment in Qatar. Although the drivers' route choices represent the main objective, it was also aimed to investigate (based on behavioral and attentional parameters) how drivers behave at first and repeated exposure to the ATIS configurations.

Three research questions have been formulated:

Q1: a) Revealed vs. stated preferences: How many drivers will take the alternative route, if delay times vs. total travel times are displayed at a freeway diversion?
b) To what extent is a reported general perceived time pressure associated with the route choice?
Q2: Is the drivers' deceleration and lateral position adjustment differently affected through the repetition of traveler information?
Q3: Does a graphical interface (color-coded GRIP) improves or worsens drivers attention allocation compared to conventional text-based VMS?

3. Methodology

3.1. Message designs

General guidelines for information provision to drivers on Qatar freeways (e.g., minimum text size, panel type, sign placement, etc.) were consulted from the Qatar Traffic Control Manual (2015). The design specifications for dynamic travel information on VMS and GRIP were consulted from guidelines published by the Dutch ministry of infrastructure and environment (Rijkswaterstaat, 2012), considering that the Netherlands is one of the few countries worldwide that apply dynamic VMS and GRIP for similar travel information and rerouting purposes. The message designs (Table 1) do follow the best practice design consideration, as summarized by Reinolsmann et al. (2020).

Table 1 presents an overview of the control phase displaying regular travel times without road works on the freeway and the updated phases of increased travel or delay times due to construction work on the main route, and the real-time travel or delay times on the alternative route. Phase 1 describes the traffic warning and alternative route suggestion, and phase 2 represents the second update due to further increase in congestion being displayed on a VMS or GRIP. To test total travel times and delay times separately, a distinction was made between phase 1a- travel times and 1b- delay times. The three text lines on the VMS are organized as recommended by Arbaiza and Lucas-Alba (2012). The freeway destination with an interchange symbol is presented on the first message line, the travel times for continuing the original route are presented on the second line and the travel time for following the alternative route (i.e., via Al Khor) to the destination is presented on the third line. In phase 1 the a) travel time or corresponding b) delay time for the main route is updated due to the work zone bottleneck. Alternatively, the same warning and rerouting message can be displayed on a GRIP with the additional advantage of activating colored segments on the map visualizing the congestion (i.e., red) and free-flow (i.e., green) conditions.

Warning phase 2 is activated if the traffic volumes on both routes are increased and the rerouting advice has contributed to 5 min delay on the alternative route due to slower driving speeds (see Table 1). The delay times on the VMS and GRIP are updated to 15 min vs. 5 min while maintaining a 10 min delay time difference between the routes. The delay time display in phase 2 would correspond with 40 min vs. 40 min as compared to 35 min vs. 35 min shown in warning phase 1a.

Fig. 1. Driving simulator at Qatar University.

3.2. Instruments

3.2.1. Driving simulator

The medium-fidelity driving simulator at Qatar Transportation and Traffic Safety Center (QTTSC) was used to collect data on driving behavior and route choices (Fig. 1). The simulator consists of the driving unit (Range Rover Evoque car), which is equipped with a force-feedback steering wheel, pedals, gearbox (automatic transmission) as well as a speedometer and indicators. Three large screens with 135° of a horizontal field of view, a resolution of 5760 × 1080 pixels, and a 60 HZ refresh rate complete the simulator. The driving scenarios were programmed with STISIM Drive 3. High-speed graphics and sound processing were further supported by the STISIM Drive tool CalPot32. The driving simulator is logging several driving parameters, for instance, longitudinal speed (m/s), decelerations, and the lateral driving position, which can be used to calculate lane changes and exit maneuvers. The driving simulator at Qatar University has been validated for speed perception through a comparison study based on drivers' speed choices in an instrumented vehicle and in the driving simulator (Hussain, Alhajyaseen, Pirdavani, et al., 2019).

3.2.2. Wearable eye tracker

The Tobii Pro Eye Tracking Glasses 2 (see Fig. 2) were used to investigate drivers' eye fixations towards the tested information display designs. The wearable eye-tracking glasses make it possible to move the head freely and contain a high-definition camera and microphone embedded in the middle of the glasses for recording the audiovisual scene in front (resolution of 1920 × 1080 pixels, at 25 frames per second [s]). The audiovisual recording is stored on a recording unit that connects to the glasses. The participant's eye gaze behavior is tracked and recorded via four sensors with a 100 Hz sampling rate (Tobii Pro, 2020). The participant is seated 1 m from the driving simulator screen, which corresponds approximately to the same distance between the driver and the calibration card, which was used to calibrate the gaze direction for every driver individually. The accuracy of the collected eye-tracking data was checked for every test drive by asking the participant to look at a particular stimulus and comparing the real stimuli position with the measured gaze position on the Tobii Pro glasses controller screen. A recalibration was eventually done if the participant's gaze position slightly deviated.

3.3. Scenario designs

Seven simulator test drives of varying lengths (5.5–7 km) were developed to investigate driver behavior for 3 VMSs and 3 GRIPs displaying warnings and travel information, and one control condition displaying regular travel times. The Fig. 3 displays a Google map screenshot of the two driving routes to Madinat Al Kaaban and the regular travel times for the original route (25 min) and an alternative route (35 min) where no work zone is present. The Fig. 4 shows the configuration of the test drives and the sign placement including static direction signs (Far Advance Direction Sign (FADS), Advance Direction Sign (ADS), Direction Sign), and the dynamic variable message signs. The dynamic travel information signs were repeated a second time before the exit as it was recommended by Castro and Horberry (2004) to confirm the displayed information and to support drivers' final route choice. Freeways exits were implemented in the filler pieces and bridges and roadside buildings were added in the simulation.

A realistic driving experience was created, which also includes normal interactions with other vehicles that drive on the freeway. The Fig. 5 displays screenshots of freeway FADS in the simulation and on the real freeway.

The surrounding vehicles were slightly falling back around 800 m before the exit to not influence the participants' route choices. Based on the displayed ATIS drivers had to decide whether they would follow the main or alternative route to reach their destination Madinat Al Kaaban. The drivers could either take the indicated exit to follow a freeway via Al Khor or continue on the current freeway. In the latter case, drivers who stayed on the initial route would encounter the entrance of the work zone. Cones were used for closing the outer lanes of the freeway and road work vehicles and construction equipment were placed alongside the road. Participants were forced to slow down due to traffic congestion at the bottleneck. The simulation drive was then ended since the route choice was made

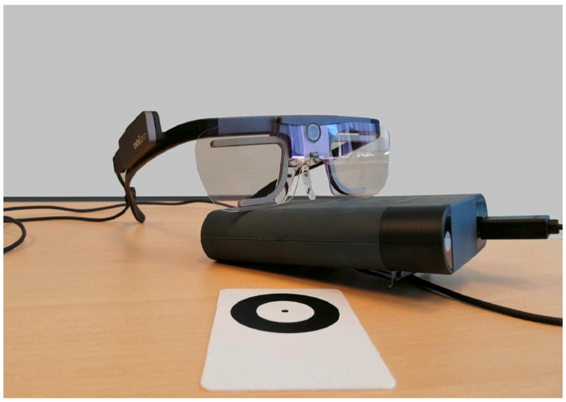


Fig. 2. Tobii Pro Eye tracking system.

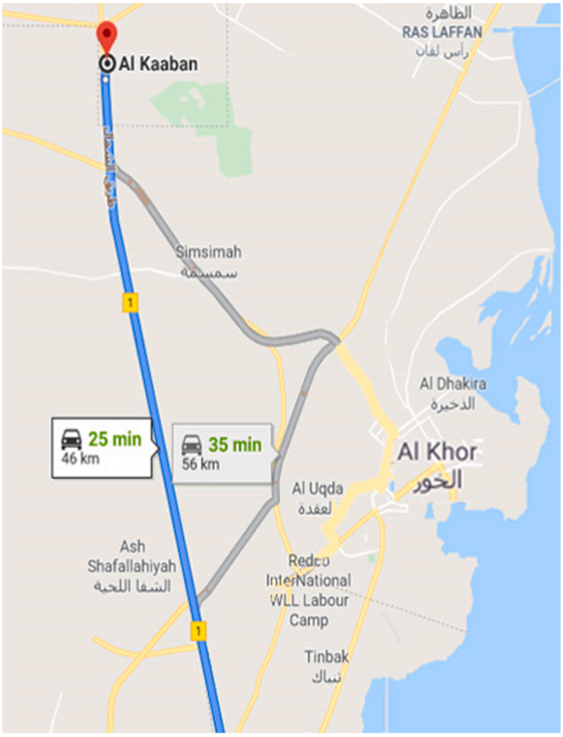


Fig. 3. Regular travel time for original and alternative route.

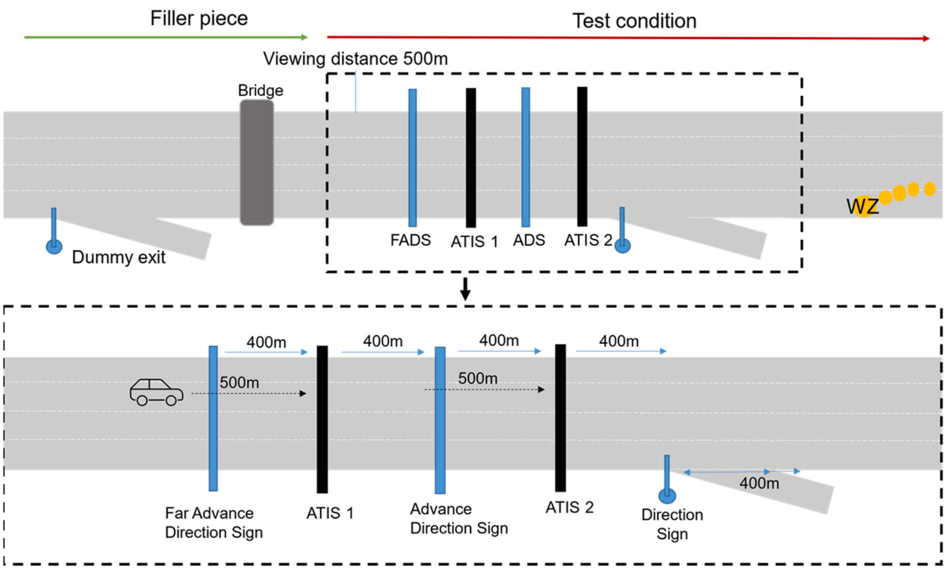
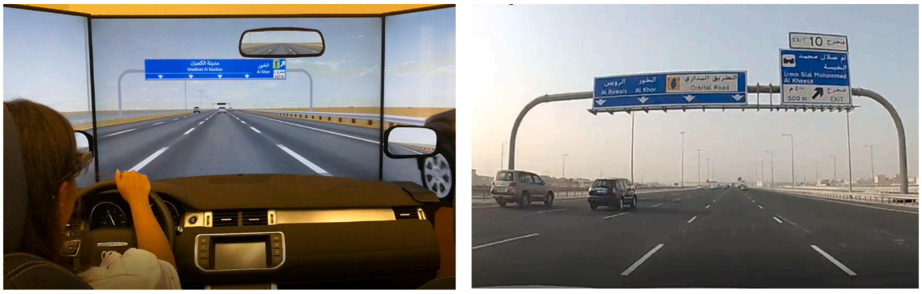


Fig. 4. ATIS configurations for scenario designs.

and participants' experience of congestion and delay due to road works was verified. Also, in case the alternative route was chosen the test drives were ended while driving on the off-ramp towards the alternative freeway.

3.4. Procedure

The participants were recruited via information leaflets, posters, and circular emails distributed at Qatar University and through social media. Drivers were also recruited via networking organizations and institutes operating in the field of freeway constructions and transportation in Qatar. The data collection period was one month. The study was approved by the ethical commission of Qatar



a) Driving simulator view b) Real freeway view

Fig. 5. Far Advance Direction Sign a) in the simulator and b) on-the real freeway.

University. Participants had to sign a consent form and received general information about the procedure of the research and the possible risk of motion sickness in a driving simulator. First, a pre-test questionnaire including demographics and questions about the driving experience and the evaluated credibility of dynamic travel information was presented. Afterward, the participants were introduced to the driving simulator. All participants completed one practice drive to get familiar with the driving controls and the simulation screen. In the next step, the eye-tracking system Tobii Pro Glasses 2 was presented to the participant. The eye-tracker calibration was conducted for every individual to make sure that the eye-tracking camera could track the pupil and deliver an accurate output capturing the drivers' eye fixations to the signs and surroundings during the test drives. After successful calibration, participants received the instruction to drive on the freeway as they would normally do in the real world. Participants were asked to drive to the destination Madinat Al Kabaan in the North of Qatar and to choose the best route based on en-route travel information. All participants started with the control scenario where no work zone was present yet, and regular travel times were displayed. The participants did not drive the full length of 25 min to the destination. Instead, the control scenario ended automatically after less than a kilometer when passing the ATIS location displaying the regular travel times for the main freeway route. Afterward, the six test drives with different warning phases for two available routes and ATIS configurations were randomized for all participants. It should be noted that the duration of every scenario drive was set to 4–5 min and stopped automatically. Therefore, the drivers' route choice experience was solely based on the ATIS travel information configuration and the experience of a congestion queue on the main route or the detour maneuver when taking the freeway off ramp. Between every test drive there was a short break of 1–2 min to load a new scenario and to reduce the risk of exhaustion or simulation sickness (Fisher, Rizzo, Caird, & Lee, 2011). Once all test drives were finalized, the participants were asked to fill in a post-test questionnaire to evaluate each travel information display on the aspect of perceived persuasiveness to comply with the alternative route suggestion. The participants were requested to indicate whether the displayed time method and ATIS type influenced their decision to take the alternative route or to stay on the current freeway. The study was completed after one hour without financial compensation.

3.5. Data processing and analysis

The IBM SPSS Statistics 26 software was used to explore the results of the questionnaires on demographic background, driving-related aspects, and the stated preferences for the tested ATIS display strategies. Furthermore, the driving parameters that were recorded in the driving simulator during the visibility distance (500 m) to the first gantry-mounted ATIS sign and the repeated gantry-mounted ATIS sign (500 m) were investigated in detail. A summary of the selected parameters in this study is presented in Table 2. These behavioral parameters can provide implications about the effect of visual distraction or attentional competition, which reduces the driver's attentional capacity to safely drive and interact with other vehicles on the freeway. Attentional competition can occur if

Table 2
Overview of driving and viewing parameters.

Research variables		
Mean speeds [km/h]	Indicator for increased crash risk and severity	Elvik, 2013; Jeihani & Ardeshiri, 2013; Timmermans, Alhajyaseen, Al Mamun, et al., 2019
SD speed	Disruption of traffic flow and increase in the risk of rear-end crashes (e.g., distraction, speed perception)	Erke et al., 2007; Hussain, Alhajyaseen, Brijs, et al. (2019); Hussain, Alhajyaseen, Pirdavani, et al., 2019
Mean Deceleration [m/s^2]	Deceleration because of driving attention demands while reading the ATIS	Erke et al., 2007; Reinolsmann, Alhajyaseen, Brijs, Pirdavani, et al., 2019
Mean lateral position [m]	Indicator for lane position and abrupt lane changes	Yan & Wu, 2014; Reinolsmann, Alhajyaseen, Brijs, Pirdavani, et al., 2019
Average eye fixation duration [ms]	Long eye fixation durations indicate difficulties in extracting information, while shorter mean durations indicate that the information can be extracted easily.	Andrychowicz-Trojanowska, 2018
Average number of eye fixations	More eye fixations = more noticeable in the environment, whereas fewer eye fixations = greater information intake per fixation	Andrychowicz-Trojanowska, 2018

the ATIS message is distracting or confusing, which might have a negative effect on the situation awareness of the drivers on high-speed freeways (Regan, Hallett, & Gordon, 2011). This interaction between the driver and the ATIS sign affects drivers' control of the vehicle and their maneuvers. For instance, Jeihani and Ardeshiri (2013), found variations in drivers' speed behavior while encountering route choice dynamic message signs.

The clear legibility distance for advance direction signs at a distance of 500 m over four lanes begins usually 300 m before the sign (Manual, 2015). Therefore, the two 500 m visibility zones were first divided into smaller zones of 50 m to calculate mean driving speeds, which is an indicator related to increased crash risk (Elvik, 2013). Also, the standard deviations of speed were calculated since high variations in speed between drivers can disrupt the traffic flow and increase the risk of rear-end crashes (Erke, Sagberg, & Hagman, 2007). Moreover, the average deceleration of drivers was investigated since drivers may reduce their speed as a consequence of too high attention demands while reading the displayed travel information (Erke et al., 2007). The mean lateral position of drivers was also considered. This is an important indicator showing whether drivers respond to the displayed information through adjustments in the lateral lane position and to investigate in which conditions drivers decided to take the suggested exit or continued their path (e.g., Yan & Wu, 2014). The driving-related parameters in driving zone 1 (before the first ATIS) and driving zone 2 (before the repeated ATIS), as shown in Fig. 6, were compared using repeated-measures analysis of variance (ANOVA).

Furthermore, two eye-tracking parameters were investigated for each condition over the visibility distance of 500 m to the signs at the first ATIS location. The average eye fixation duration was extracted as an indicator for the drivers' ease or difficulty to retrieve information from the signs, whereas the average number of eye fixations per condition is an indicator for how noticeable the sign designs are and whether the information intake was efficient (Andrychowicz-Trojanowska, 2018). To extract the eye-tracking data, the Tobii Pro Glasses footage over the 500 m visibility distance to the first ATIS was exported as.mp4 files using Tobii Pro analysis software version 1.130. The eye-tracking precision of the data sample was examined to see how reliable the eye tracker was to reproduce the same gaze point measurements among all participants (Holmqvist, Nyström, Andersson, Dewhurst, Jarodzka, & Van de Weijer, 2011). The gaze point measurements revealed relatively high reliability. The drivers' eye-tracking sample precision ranged from 73% to 98%. In total, 87.5% of the drivers' gaze points were reliably measured with a precision of 85% or higher. The audiovisual files for each participant contain an eye-tracking overlay in the form of a red circle that represents a driver's attentional focus at any point in the simulation drive. The Tobii analysis software allows for screenshot-based mapping of drivers' eye fixations (and its duration) on the defined area of interest (e.g., gantry mounted travel information signs). The mapping procedure was done manually to guarantee that drivers were fixating the area of interest (AOI) from varying distances to the ATIS and in case of head movements affecting the glasses' built-in camera position. The Tobii analysis software provides the option for an attention filter to be applied to the metrics data. The Tobii I-VT attention filter extracts data when the fovea (i.e., the central point of the pupil providing the clearest vision) is stabilized on the AOI. This attention filter is usually recommended for eye tracking in dynamically moving scenarios (Tobii Pro, 2020). A boxplot analysis was conducted to detect outliers. Extreme values that exceeded three standard deviations were replaced by the median values to normalize the data (Costa, Simone, Vignali, Lantieri, & Palena, 2018).

4. Results

4.1. Participants

In total, 80 drivers participated in the driving simulator and eye-tracking study. No participants suffered from simulation sickness. In total, twenty-nine different nationalities participated in this study. The mean driving age was 31 years, and 80% of all participants were male. The majority of drivers held a Qatar driving license for more than two years with a fairly even representation of average driving km/year in the low, middle, and high driving experience categories. The sample was a good representation of the heterogeneous driving population in the State of Qatar, with.

7% of drivers being Qatari nationals and a higher male representation among drivers (Soliman, Alhajyaseen, Alfar, & Alkaabi, 2018; Timmermans, Alhajyaseen, Al Mamun, et al., 2019; Timmermans, Alhajyaseen, Reinolsmann, et al., 2019; Timmermans et al., 2020). The demographic characteristics of the 80 drivers are summarized in Table 3.

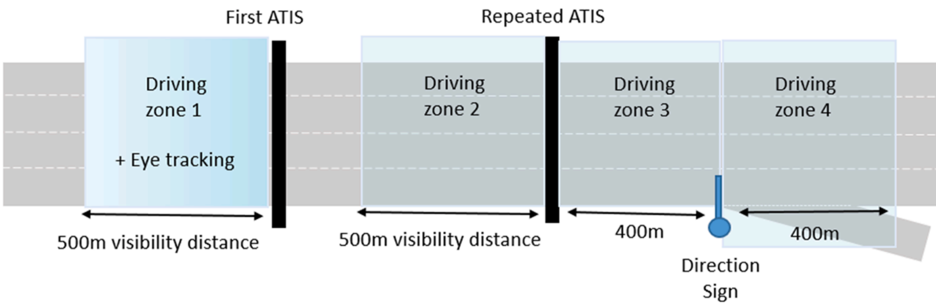


Fig. 6. Driving zone included in analysis.

4.2. Drivers' route choices

The drivers' detour rate is shown in Table 4, indicating the percentage of drivers taking the alternative route. No drivers were taking the alternative route if no road works warning was displayed (e.g., control). In the control scenario, drivers did only receive the regular total travel times for both routes to Madinat Al Kaaban. Condition 1 presents a road work warning, and the total travel times were updated with a delay of 10 min on the original route. Equal total travel times for both routes were displayed on the VMS and GRIP.

The results show that this difference in panel design influenced 61.25% of drivers to take the alternative route, whereas only 36.25% of drivers took the alternative route in case total travel times were shown on the VMS. In condition 2, the total travel times were replaced by delay times, while the traffic information remained the same as compared to condition 1. As we can see from the results, the percentage of drivers taking the alternative route was doubled to 73.75% when delay times were displayed on the VMS. Also, the percentage of drivers taking the alternative route increased clearly from 61.25% to 81.25% if the delay time was shown on the GRIP. In condition 3 (updated second phase), the traffic congestion has further increased to 15 min, but 5 min longer travel times are also displayed for the alternative route due to more traffic. The results indicate that there is only a decrease of 5% in drivers taking the alternative route (68.75%) if an increased delay was shown on the VMS. Simultaneously, 72.5% of the drivers took the alternative route if the additional delay was shown on a GRIP. Whether a VMS or GRIP was used did not differ much since the orange color shown on the alternative route was simply visualizing the additional delay.

The McNemar test (see Table 5) was conducted to investigate whether a reported 'perceived time pressure' among drivers can be associated with their route choices in the ATIS display conditions. The drivers had to indicate before the driving simulation task how often they felt time pressure while driving using a Likert scale from 1 (never) to 5 (almost every time). The answers were coded into a dichotomous variable. The results showed that there was a significant association between the level of perceived time pressure and the route choice they made in the test conditions. The drivers who reported low perceived time pressure were more likely to continue the freeway route, whereas drivers who generally reported higher perceived time pressure were rather associated with taking the detour to avoid the road works and follow the uncongested route. This association was significant for all test conditions except for the VMS in warning phase 1, which indicates that perceived time pressure is not associated with the route choice decision in case two equal total travel times are displayed on a VMS.

4.3. Drivers' stated preferences

Participants were asked about their previous experience with dynamic travel information and had to indicate the frequency of how often they took an alternative route in case of congestion on the main route. The Fig. 7 shows that 64% of drivers in this study consider dynamic travel information as reliable. Besides, Fig. 8 highlights that 43.8% of the drivers would sometimes take a detour, whereas up to 41.3 % indicated to take a detour often or almost every time.

Furthermore, participants had to evaluate each dynamic traffic information panel design they had seen in the driving simulation and indicate whether this ATIS design motivated them to take the alternative route to the destination. The results are summarized in Fig. 9.1. The percentage of drivers who stated to be motivated taking the detour (i.e., green bar) can be compared with the actual percentage of drivers taking the alternative route in the simulator (see Fig. 9.2).

Firstly, it can be seen in Fig. 9.1a that 26.3 % of drivers think that the total travel time display on the VMS is motivating them to take the alternative route. Interestingly, this is 10% less than the actual percentage of drivers who took the alternative route in the simulator. Fig. 9.1d shows that>51% of all drivers stated to be motivated to take the detour if total travel times were shown on the GRIP with similar travel times for both routes.Still, the actual percentage of drivers who took the alternative route in the simulation is + 10 % (Fig. 9.2). Secondly, the display of delay times was motivating drivers to take the detours irrespective of the ATIS panel type, indicating that delay times lead to 72.5% of drivers taking the detour if shown on a VMS (see Fig. 9.1b) or 77.5% if shown on a GRIP (see Fig. 9.1e). The stated preference data are therefore comparable with the percentage of drivers who took the detour in the simulator. Thirdly, the additional delay of 5 min on both travel routes shows an almost equal distribution (53.8%) of drivers stating to take the detour if displayed on the VMS (Fig. 9.1c) and the GRIP (Fig. 9.1f). Interestingly, the percentage of drivers taking the

Table 3
Demographics of sample (n = 80).

Gender:		**Profession:**		**Average driven km/ year**	
Male:	80.0%	*Employed full time*	47.5%	*< 10,000 km*	33.8%
Female:	20.0%	*Employed part-time*	5.0%	*10,000 to 19,999 km*	27.5%
Age		*Businessman/woman*	2.5%	*> 20,000 km*	38.8%
Range	18–65 years	*Unemployed*	1.3%	**Familiarity with road network**	
Mean	30.9 years	*University Student*	41.3 %	*Very unfamiliar*	12.5%
SD	10.9 years	*Housewife/househusband*	2.5%	*Somewhat familiar*	17.5%
Origin		**Qatar driving license**		*Familiar*	30.0%
Arabian	43.75%	*> 2 years*	73.8 %	*Very familiar*	40.0%
Western	22.5%	*< 2 years*	26.2 %		
Asian	25.0%	**License country characteristics**			
African	8.75%	*Right hand traffic*	70.0%		
		Left hand traffic	30.0%		

Table 4
Percentage of drivers taking the exit/ alternative route.

Test conditions	VMS	GRIP
Control	0%	
1 – Total travel time	36.25%	61.25%
2 – Delay time	73.75 %	81.25%
3 – Increased delay	68.75%	72.50%

Table 5
McNemar Test of drivers' perceived time pressure & ATIS route choice.

Phase	**Condition**	**Route Choice**	**Perceived time pressure**		**Total drivers 80**	**p-value** (2-sided)
			Low (%)	**High (%)**		
Phase 1a (total travel time)	**VMS 1**	Continue	35 (69%)	16 (31%)	51	> 0.999
		Change route	17 (59%)	12 (41%)	29	
	GRIP 1	Continue	28 (90%)	3 (10%)	31	< 0.001*
		Change route	24 (49%)	25 (51%)	49	
Phase 1b (delay time)	**VMS 2**	Continue	16 (76%)	5 (24%)	21	< 0.001*
		Change route	36 (61%)	23 (39%)	59	
	GRIP 2	Continue	12 (8%)	3 (2%)	15	< 0.001*
		Change route	40 (62%)	25 (38%)	65	
Phase 2 (delay both routes)	**VMS 3**	Continue	18 (72%)	7 (28%)	25	< 0.001*
		Change route	34 (62%)	21 (38%)	55	
	GRIP 3	Continue	17 (77%)	5 (23%)	22	< 0.001*
		Change route	35 (60%)	23 (40%)	58	

* Significant at $\alpha < 0.001$.

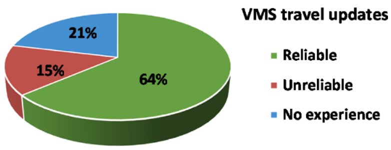


Fig. 7. Drivers' evaluation of travel updates.

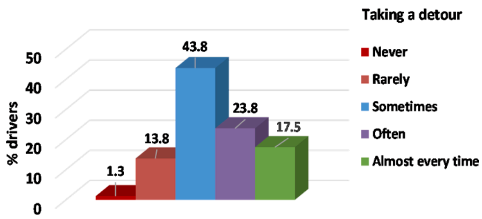


Fig. 8. % Drivers following detours.

alternative route in the simulator was higher by 15% till 18.7%, especially in the case of GRIP (see Fig. 9.2). This indicates that drivers who stated to be unsure (23.8% and 26.3% in Fig. 9.1c and f) did eventually take the detour in the simulator.

When drivers were asked to directly compare the VMS or GRIP configurations for 'total travel time', 'delay time', and 'increased delay', it was shown that GRIPs were evaluated as the preferred display type for total travel times or delay times (see Fig. 10) since these panels provide more context information about the travel distance and congestion. The increased delay times plus 5 min on the alternative route (see Fig. 10c) did not result in any difference between the GRIP and VMS and were considered equally suitable.

4.4. Driving behavior before first ATIS location

The 50 m zones within the 500 m visibility distance to the traffic information signs were visualized in Figs. 11 - 12. The data for VMS conditions are represented by solid lines, and the data for GRIP is shown in dashed lines. The Fig. 11 shows the drivers' mean speeds over 50 m zones before the information displays at the first ATIS location.

It is shown that mean speed in the control condition is relatively stable throughout the traveled distance, which can be ascribed to the fact that the regular travel time without any incident warning was displayed first to all participants. In all other test drives, the speed reduction started already when the ATIS conditions became visible. A repeated-measures ANOVA with Bonferroni corrections

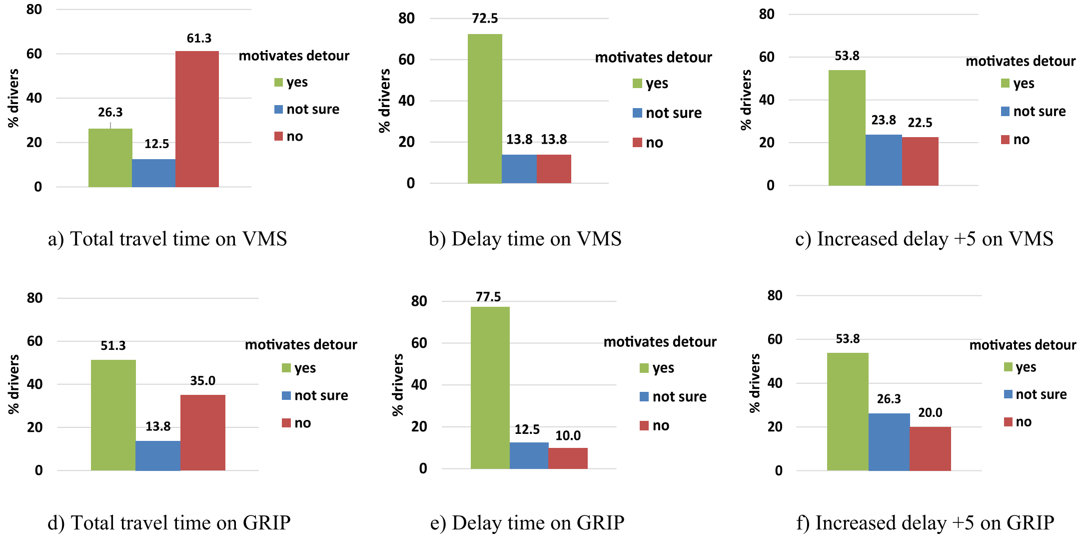


Fig. 9.1. Drivers' stated motivation to take the alternative route after sign exposure.

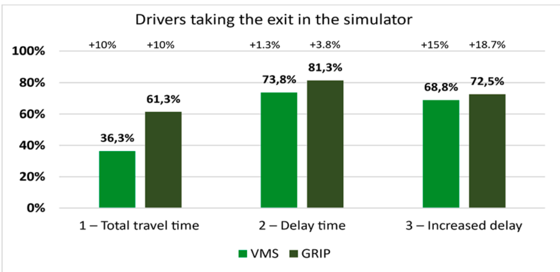


Fig. 9.2. Drivers taking the alternative route in in the simulator.

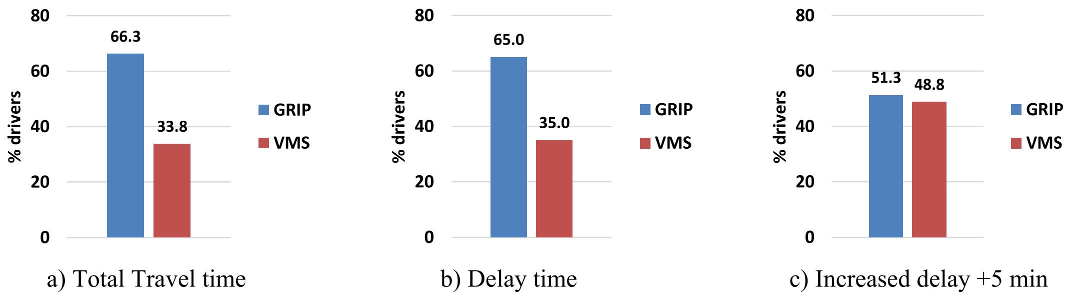


Fig. 10. Stated preferences for time display methods on VMS vs. GRIP.

revealed significant differences in the mean driving speeds at 450 m for the ATIS condition 'VMS 2 delay' ($F_{(5,401)} = 7.45$, $p = 0.002$, $\eta\rho^2 = 0.086$) and 'GRIP 2 delay' ($F_{(5,401)} = 7.45$, $p = 0.043$), 'VMS 3 increased delay' ($F_{(5,401)} = 7.45$, $p < 0.001$) and 'GRIP 3 increased delay' ($F_{(5,401)} = 7.45$, $p < 0.001$) as compared to the control condition. The VMS 1 and GRIP 1 travel times were not significantly different from the control conditions. However, for the last 50 m to the sign significant differences with the mean driving speed of the control condition were only found for 'GRIP 1 travel time' ($F_{(5,393)} = 4.04$, $p = 0.018$, $\eta\rho^2 = 0.05$) and 'GRIP 2 delay' ($F_{(5,393)} = 4.04$, $p = 0.002$), given the green alternative route suggestion for this warning phase.

The Fig. 12 presents the drivers' average deceleration over the 50 m zones before the display conditions.

The control condition and 'VMS 1 travel times' follow a different deceleration path as compared to the other conditions with, particularly, the control condition accelerating 250 m before the ATIS location when no warning was provided.

It can be summarized that the warning signs resulted in deceleration behavior already from 450 m before the signs, which can be attributed to the visible red warning pictogram. At 350 m before the ATIS location, the drivers' deceleration has stopped for the 'VMS 1

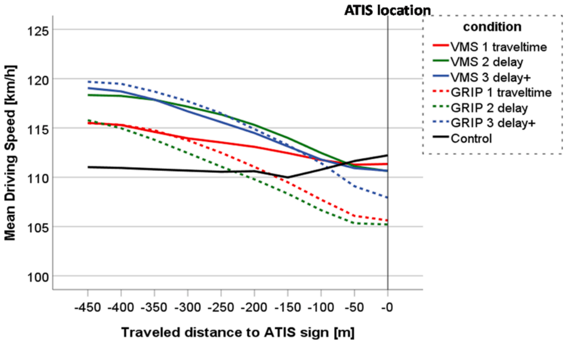


Fig. 11. Drivers' means speeds before the first ATIS location.

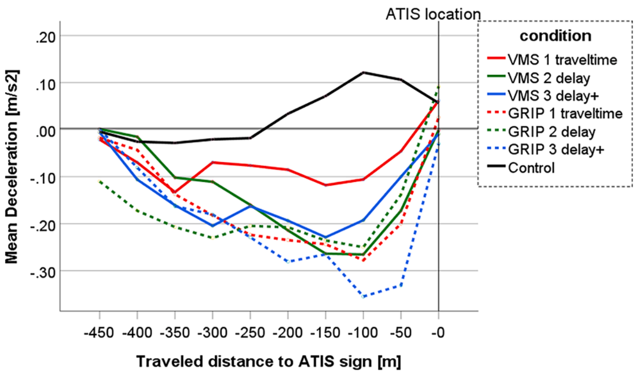


Fig. 12. Drivers' mean deceleration before the first ATIS location.

travel times' condition, which indicates that drivers were able to read the equal travel time information for both routes. Around 150 m before the sign, an acceleration is taking place in all conditions except for the control design. This means that generally, the drivers decelerated to read the information and then accelerated to maintain their regular speed.

4.5. Repetition of ATIS: driving behavior until off-ramp

The average driving behavior during the first ATIS exposure of 500 m and the second (i.e., repeated) ATIS exposure during the 500 m sign visibility distance was compared. A repeated measure multivariate analysis of variance (MANOVA) was conducted to investigate the impact of all tested sign conditions on driving behavior during the two ATIS exposure zones. Table 6 shows that the results of the main and interaction effects between the conditions and the two ATIS driving zones were all significant. The significant interaction effect between condition and ATIS zone on the driving parameters of interest was further investigated using repeated measures analysis of variance (ANOVA). The p-values were set at 0.05 and the repeated measures ANOVA's were Bonferroni corrected.

Table 7 displays the significant effects on mean speed, mean deceleration, and the mean lateral position, but not for speed variations (i.e., SD speed), which indicates that no display condition resulted in speed variations among drivers during first or repeated ATIS exposure. The pairwise comparisons of the matched mean speeds between the first ATIS and repeated ATIS location showed no significant differences, which indicates that a similar speed reduction path was measured over both visibility distances of 500 m to the ATIS. In the following section, deceleration, and the lateral position of drivers until the freeway diversion were investigated in more detail to reveal the impact of the first and repeated ATIS location.

Table 6
MANOVA: main and interaction effects.

MANOVA				
Effect	F	dfs	p-value	$\eta\rho^2$
Condition	8.301	24; 1644	<0.001**	0.095
ATIS driving zone	62.558	4; 76	<0.001**	0.767
Condition × ATIS zone	4.569	24; 1644	<0.001**	0.055

** Significant at $\alpha < 0.001$.

Table 7
ANOVA: driving parameters.

Within-Subjects Effects for Condition × ATIS Zone (Greenhouse-Geisser)				
Effect	F	dfs	p-value	ηρ²
Speed	2.964	5; 432	0.010*	0.036
SD speed	0.767	4; 335	0.554	0.010
Deceleration	2.996	5; 408	0.011*	0.037
Lateral Position	11.673	4; 441	< 0.001**	0.129

* Significant at $\alpha < 0.05$.
** Significant at $\alpha < 0.001$.

4.5.1. Drivers' mean deceleration

The Fig. 13 shows the drivers mean deceleration per condition measured during the visibility distance of the first ATIS (zone 1), the repeated ATIS (zone 2) as well as until the exit sign (zone 3), and until passing the off-ramp (zone 4).

Repeated measures Bonferroni corrected pairwise comparisons for the mean deceleration (recorded before the first ATIS zone) revealed that a significantly larger mean deceleration was found in all test conditions as compared to the control condition. Also, a significant deceleration difference of 0.10 m/s^2 was found between 'VMS 1 travel times' and the control condition with regular travel times ($F_{(5;390)} = 11.85$, $p = 0.031$). However, 'VMS 1 travel times' resulted in lower decelerations as compared to all GRIP conditions. More specifically, there was a significant difference of 0.09 m/s^2 stronger deceleration for 'GRIP 1 travel time' ($F_{(5;390)} = 11.85$, $p = 0.032$), 0.10 m/s^2 stronger deceleration for 'GRIP 2 delay' ($F_{(5;390)} = 11.85$, $p = 0.03$) and 0.13 m/s^2 stronger deceleration for 'GRIP 3 increased delay' ($F_{(5;390)} = 11.85$, $p < 0.01$) as compared to 'VMS 1 travel times'. This indicates that the higher deceleration in the GRIP conditions led to lower (but rather insignificant) average speeds compared to the VMS displaying equal travel times. Most importantly, the display designs of the GRIPs captured the driver's attention resulting in increased alertness to prepare for driving adjustments before the freeway diversion.

A comparison between deceleration behavior at the first ATIS location and the repeated ATIS location shows that there were significantly lower deceleration rates (i.e., acceleration) for the repeated 'VMS 2 delay' ($F_{(9;725)} = 12.39$, $p = 0.026$), repeated 'GRIP 1 travel time' ($F_{(9;725)} = 12.39$, $p = 0.001$) and repeated 'GRIP 2 delay' ($F_{(9;725)} = 12.39$, $p = 0.018$), whereas no significant difference in deceleration was found for the other conditions at both ATIS locations. Drivers decelerate to read the ATIS information. The fact that drivers were decelerating less strongly in the VMS 2 and GRIP 2 'delay' conditions as well as for the 'GRIP 1 travel time' suggests that the displayed information has already been successfully processed during the information intake at the first ATIS location.

4.5.2. Drivers' mean lateral position on the freeway lanes

The Fig. 14 summarizes the drivers' mean lateral lane position during the 500 m visibility distance to the first ATIS location (zone 1) and the repeated ATIS location (zone 2). Also, the mean lateral lane position until the ramp exit sign (zone 3) and until passing the off-ramp diversion (i.e., zone 4) are visualized in Fig. 14. In all scenarios drivers did freely choose their position on the driving lanes (inner lane = 4 and outer lane = 1). The mean lateral lane position of all drivers was averaged for each driving zone for a better comparison of the driving paths among the ATIS conditions and the lateral maneuvers in every driving zone.

The repeated measures pairwise comparisons of drivers' mean lateral position in the first ATIS zone and the repeated ATIS zone resulted in significant differences for all warning and travel advice conditions ($F_{(8;636)} = 41.91$, $p < 0.001$) but not in the control condition. Within the repeated ATIS zone, all test conditions led to a significant change in the lateral lane position as compared to the control condition. Moreover, the 'GRIP 2 delay' resulted in a significant lateral position change of an additional 1.62 m to the outer lane than the 'VMS 1 travel times' ($F_{(5;431)} = 5.77$, $p < 0.01$), which can be an indicator for drivers' route adjustment intention.

The percentage of drivers who conducted at least one lane change towards the outer lanes after passing the first ATIS location is

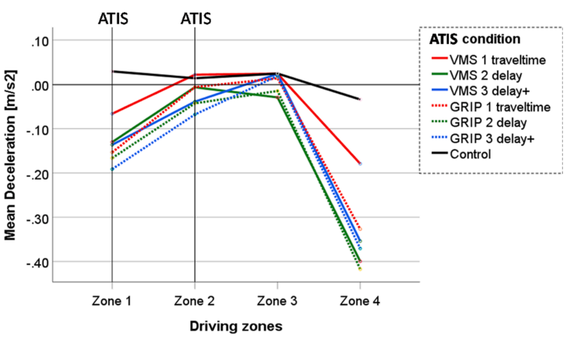


Fig. 13. Mean deceleration rate over 4 driving zones*. *Note: Driving zone 1 = 500 m visibility distance to first ATIS; Driving zone 2 = 500 m visibility distance to repeated ATIS; Driving zone 3 = 400 m distance until exit sign; Driving zone 4 = 400 m distance until passing off-ramp (as illustrated in Fig. 6).

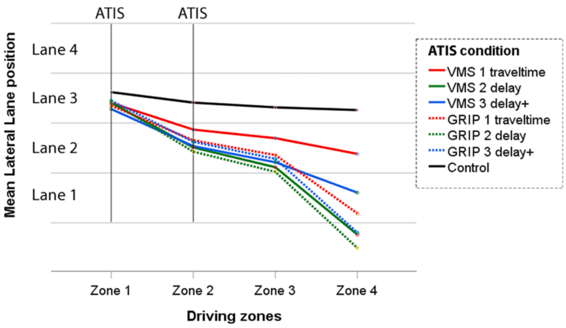


Fig. 14. Mean lateral position over 4 lanes (each ~ 3.65 m) and 4 driving zones*. *Note: Driving zone 1 = 500 m visibility distance to first ATIS; Driving zone 2 = 500 m visibility distance to repeated ATIS; Driving zone 3 = 400 m distance until exit sign; Driving zone 4 = 400 m distance until passing off-ramp (as illustrated in Fig. 6).

summarized in Table 8. A lane change was defined for a driver when the lateral position values changed at least by 3.65 m before reaching the second driving zone (visibility distance to repeated ATIS). The 3.65 m corresponds to the predefined freeway lane width. The results show that GRIPs of all phases motivated a lane change among more than half of the drivers towards the outer lane after passing the first ATIS gantry. A similar lane change effect has also been achieved by VMS 2 displaying delay times.

It can be summarized that 64–69% of the drivers conducted at least one lane change to the outer lanes after passing the VMS 2 and GRIP 2, displaying delay at the first ATIS location. This shows that 64 % of the 74% of drivers who took the alternative route did already conduct a lane change to the outer lane after the first exposure to 'VMS 2 delay' and 69% of the 81% of drivers who took the alternative route did already complete at least one lane change to the outer lane after the first exposure to 'GRIP 2 delay'.

4.6. Drivers' attention to the sign displays

The recorded eye-tracking data of all drivers were used to investigate how long and how often the drivers would look at the travel information signs during the visibility distance of 500 m to the first ATIS location. The eye fixation duration and the number of eye-fixations to the dynamic travel information signs were visualized using boxplots. The data dispersion is presented in four quartiles, including minimum values, first quartile, median, third quartile, and maximum values. The average number of eye fixations on the signs during the visibility distance of 500 m to the first ATIS location is shown for each display condition in Fig. 15. The boxplots per condition display the data dispersion in four quartiles as well as a small cross for the mean values. It can be seen from the boxplots that the average number of eye fixations (indicated by the cross) is 5 to 6 times on all travel information signs. Particularly, the VMS 3 and GRIP 3 displaying increased delay show that the VMS led to a higher number of eye fixations with a shorter fixation duration (mean: 1.27 s, SD: 0.64 s), whereas a lower number of eye-fixations is reflected in longer eye fixation durations (mean: 1.98 s, SD: 1.43 s) over the travel distance of 500 m.

The average eye-fixation duration to all sign conditions is shown in Fig. 16.

The mean value of each condition is marked by a small cross in the boxplot, and the descriptive values are presented on the side. The results of the mean values indicate that the average eye fixation duration is below 2 s for all conditions with the longest mean eye fixation durations for 'GRIP 1 travel time' and 'GRIP 3 increased delay'. It can also be seen from Fig. 16 that the lowest recorded eye fixation duration is 100 ms, which is a typical cut-off value in eye movement research to filter out saccades that don't guarantee information intake (Costa et al., 2018; Holmqvist et al., 2011).

A Shapiro–Wilk test of normality revealed that the eye fixation duration data were non-normally distributed with skewness to higher values. Since a repeated measures design was applied, we decided to use a Friedman test to detect differences among the fixation durations to the sign designs. The Friedman test revealed significantly different eye fixation durations $\chi2(6) = 42.59$, $p < 0.001$. Afterward, a post hoc analysis using the Wilcoxon signed-rank test was conducted with a Bonferroni adjustment. For this purpose, the p-value 0.05 was divided by the 9 multiple tests and set at a significance level $\alpha < 0.006$ (Field, 2013). The results summarized in Table 9 indicate that 'GRIP 1 travel time' leads to significantly longer eye fixation durations (466 ms) as compared to 'VMS 1 travel time'.

Furthermore, the results confirm that 'GRIP 3 increased delay' is significantly different from 'VMS 3 increased delay' by an additional 716 ms. Interestingly, 'GRIP 2 delay' displaying zero delays for the alternative route is not significantly different from the

Table 8
% drivers conducting a lane change to the outer lanes after passing the first ATIS.

Condition	VMS	GRIP
Control	22.5%	
1 – Total travel time	36.25%	51.25%
2 – Delay time	63.75%	68.75%
3 – Increased delay	48.75%	58.75%

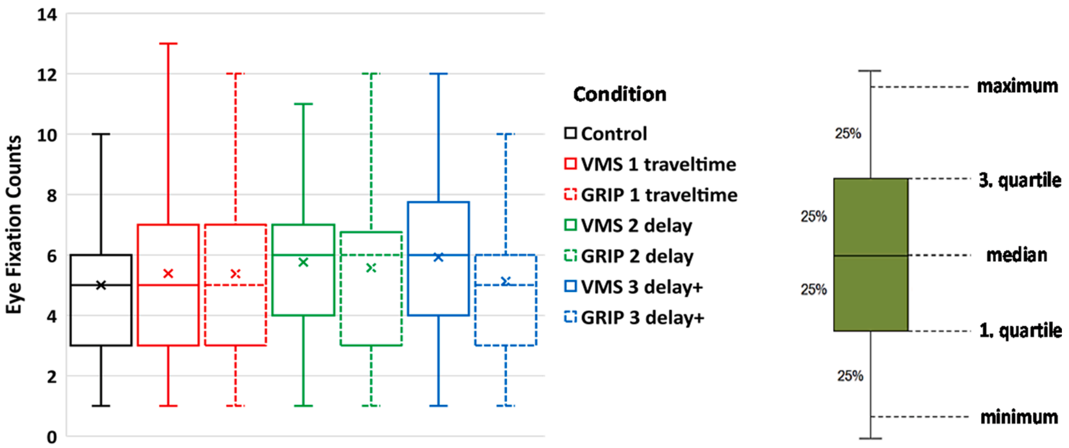


Fig. 15. Average number of eye-fixations.

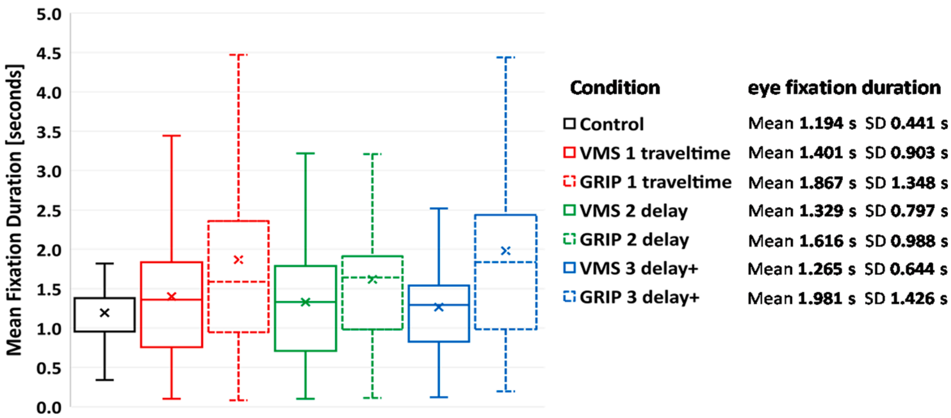


Fig. 16. Average eye-fixation duration.

'VMS 2 delay' (see again Fig. 12). Moreover, all VMS scenarios have insignificantly different eye fixation durations as the control condition despite different time display methods and an additional warning pictogram. In contrast, the GRIP scenarios do all result in significantly different eye fixation durations than the control condition due to the higher number of new information units. No significant differences between the GRIP designs were found. These results indicate that VMSs generally require lower eye fixation durations compared to GRIP except for the condition 'GRIP 2 delay'. When displaying a delay time of zero minutes for the alternative route (phase 1), the VMS and GRIP require similar attention (in terms of fixation durations). An explanation for this insignificance can be that despite shorter mean eye fixation durations for 'VMS 2 delay', the dispersion of eye fixation durations was similar with 'GRIP 2 delay', which suggests that GRIPs displaying zero delays and a green color for the alternative route are easily interpretable. A significantly greater dispersion was found for the eye fixation durations to the other GRIP conditions.

5. Discussion

The ATIS provides real-time travel information and warnings to prepare drivers of temporary work zone congestions with the option to indicate an alternative uncongested route with equal travel times. The VMS and GRIP are important components of ATIS because they can dynamically present and update travel information in different ways. Drivers benefit from traveler information since it establishes certainty regarding other personal, safety, or psychological factors (Zhang & Levinson, 2008). The same travel time ratio between the direct route and an alternative freeway route was displayed using different time display methods (i.e., total travel time vs. delays) and two rerouting update phases (i.e., free-flow alternative route vs. delay on alternative route). In total, 6 ATIS conditions were tested in the driving simulator: VMS 1 and GRIP 1 'total travel time', VMS 2 and GRIP 2 'delay', and VMS 3 and GRIP 3 'increased delay' on both routes. For all conditions, the travel time ratio remained constant between both freeway routes.

Table 9
Wilcoxon signed-rank test for eye fixation durations: multiple comparisons.

	GRIP 1 vs. VMS 1	GRIP 2 vs. VMS 2	GRIP 3 vs. VMS 3	VMS 1 vs. Control	VMS 2 vs. Control	VMS 3 vs. Control	GRIP 1 vs. Control	GRIP 2 vs. Control	GRIP 3 vs. Control
Z	−3.199	−2.465	−4.235	−1.703	−1.189	−0.610	−3.890	−3.185	−4.178
p-value	0.001*	0.014	<0.001*	0.089	0.234	0.542	<0.001*	0.001*	<0.001*

* Bonferroni corrected significance at $\alpha < 0.006$.

5.1. Revealed vs. Stated preferences: How many drivers will take the alternative route, if delay times vs. Total travel times are displayed at a freeway diversion?

Phase 1 – free flow on the alternative route.

The drivers' route choices in the simulator revealed that 73.75% of drivers took the alternative route if delay times were displayed on a VMS. If delay times were displayed on a color-coded GRIP, the number of drivers taking the alternative route (colored in green) was further increased to 81.25%. This indicates that the displayed delay time method was most convincing for drivers to take the alternative route irrespective of the ATIS panel type. The results from the stated preference survey support the revealed route choices since most drivers stated to be motivated to take the detour if delay times are displayed either on a GRIP (77.5%) or VMS (72.5%). It appears that the perception of zero delays for the free flow alternative route is used as a heuristic to follow the fastest unimpeded route (Ben-Elia & Shiftan, 2010). Possible explanations are that a non-delayed detour seems to be evaluated as time-saving over a 10 min delayed route even if, in reality, it would make no difference due to the longer travel distance resulting in similar total travel times (Reinolsmann et al., 2020). In particular, the GRIP travel recommendation highlighted through the free flow green coloring of the non-delayed alternative route did increase the drivers' compliance to the route advice despite the additional travel distance. This indicates that the green color and zero delay indication serves as a nudging signal towards the alternative route. These findings complement other studies that tested ATIS with green colored route segments (Yan & Wu, 2014, Li et al., 2014) or font color for urban roads of equal distances (e.g., Ringhand & Vollrath, 2018, 2019). Instead of total travel times, our study advises to display zero delay times to communicate advantages of a detour in terms of traffic flow and perceived reliability (Moghaddam et al., 2019). Therefore, a zero-to low delay indication can assure a reliable link performance irrespective of the panel type.

Phase 2 – slower traffic on the alternative route.

In case the delay times increase to 15 min due to road works on the original route and 5 min on the alternative route (i.e., slower traffic), 68.75% of drivers took the alternative route if displayed on a VMS, and 72.5% of drivers took the alternative route if displayed on a GRIP. This indicates that the difference in delays still motivated the drivers' decision to take a detour. The percentage of drivers taking the alternative route was even slightly higher in the simulator than indicated in the stated preference survey, where only 53.8% of the drivers were willing to take the alternative route if the travel information was updated by an additional 5 min delay on both routes. These results stand in contrast to the driving simulator study of Moghaddam et al. (2019), where total travel times were displayed for all routes. The authors found that significantly fewer drivers took a certain route in the simulator as compared to the stated route choice in the survey. In this study, it is expected that the difference in delays for both routes was used for decision making, which corresponds to the 10 min difference ratio between routes as a general threshold that influences drivers' willingness to consider an alternative route in Qatar (Reinolsmann et al., 2020). Similar rerouting percentages were also found by Ran et al. (2004), who found that about 70% of U.S. drivers would take an alternative freeway route if the VMS displays a traffic delay of 15 min due to construction work.

5.1.1. To what extent is a reported general perceived time pressure associated with the route choice?

Most drivers perceived dynamic travel information as a reliable information source, and many drivers are used to frequent detours due to congestion and construction sites on the Qatar freeway network during the past years. The revealed route choices showed that drivers who generally scored higher in perceived time pressure were associated with taking the alternative route to avoid the road works and follow the uncongested route, whereas drivers with low perceived time pressure were rather associated with continuing the freeway route. These results are confirmed by Ringhand and Vollrath (2018), who reported that drivers comply less to travel time recommendations in the absence of time pressure. Also, Moghaddam et al. (2019) found that work trips influenced the driver route choice behavior, since drivers tend to take the more reliable non-delayed toll route to get to work on time. This association was not applicable for VMS displaying equal travel times since a route choice was made under greater uncertainty about the travel conditions on the alternative route.

5.2. Is the drivers' deceleration and lateral position adjustment differently affected through the repetition of traveler information?

There were no differences in average driving speeds between the first ATIS and repeated ATIS location before the freeway diversion. Also, no speed variations were found between the first and repeated ATIS location, which indicates that drivers entered both ATIS visibility zone at higher speeds and reduced their speeds homogeneously while reading the warning and travel information. These results suggest a low risk of rear-end crashes for all ATIS design implementations (Erke et al., 2007). Instead, differences in deceleration behavior and lateral lane position were found between the first and repeated ATIS zone. The VMS and GRIP both displaying delays as well as the GRIP displaying travel times did result in fewer decelerations at the repeated ATIS location as compared to the first ATIS location. This provides evidence for better readability and information comprehension for the delay time displays irrespective of panel type as well as for the GRIP displaying a green color on the alternative route in case of equal total travel times. For these designs, drivers were able to successfully process the information during the first exposure. Therefore, drivers did not significantly decelerate anymore at the second ATIS location. Furthermore, GRIP and VMS displaying zero delays (phase 1) resulted in more lane changes after passing the first ATIS location, which was then reflected in the high percentage of drivers taking the freeway exit for the alternative route.

Phase two: When the VMS was updated to phase two, a lower percentage of drivers performed a lane change after the first ATIS location. The percentage of drivers taking the exit was only increased after passing the repeated ATIS location and direction sign by an additional 20%. This indicates that some drivers were not decisive yet and confirmed their route choice after the repeated ATIS location. These behavioral results are also reflected in the stated preference survey, where 23.8% – 26.3% of drivers were not sure whether they would take the alternative route when the traffic delay was increased for the alternative route. Nevertheless, higher travel time losses on the main route were evaluated as more important than the loss on the alternative route. Simultaneously, the delay time difference between the two routes suggests a gain for the drivers choosing the alternative freeway route. Similar observations have been made by Ringhand and Vollrath (2018; 2019), who displayed urban travel advice directly on the screen of a driving simulator. Moreover, our study has shown that repeating travel advice with additional info units can benefit hesitant drivers to confirm their final route choice. Sharples et al. (2016) previously reported increased confidence when VMS travel information is repeated on the road. We have seen that this travel information repetition can also benefit drivers if presented on a GRIP. However, no repetition seems necessary if zero delays for the alternative route are displayed on either panel.

5.3. Does a graphical interface (color-coded GRIP) improve or worsen drivers' attention allocation compared to conventional text-based VMS?

The eye-tracking analysis has shown that VMS do generally result in lower eye fixation durations than GRIPs. Interestingly, there is no substantial difference between VMS and GRIP 'zero delay' displays. Despite the novelty of the GRIP and its additional color units, drivers paid similar visual attention to the delay time display on VMS and GRIP. In line with Ringhand and Vollrath's (2019) argumentation, the work zone delay has been framed as a time loss, whereas the zero delays represent the gain frame that has been visualized through green color (i.e., free-flow traffic) on the GRIP. In contrast, the increased delay update in phase 2 resulted in significant differences in attention demand for the VMS and the GRIP with longer fixation durations for the GRIP displaying slow traffic in orange on the alternative route. Malkoc, Hedgcock, and Hoeffler (2013) have investigated the process of decision making in the context of undesirable alternatives. The authors highlighted that the detected negative ("warning") stimuli would receive more attention in the information processing stage. If both displayed route options appear to be unattractive, the anticipated outcomes are associated with negative emotions, which influences a person to pay more attention to the details and to seek more information before making a choice (Malkoc et al., 2013). This means that the additional information units shown on a GRIP (i.e., additional orange-colored delay and a distance-wise longer detour) are likely to increase the driver's visual processing time since both routes present unattractive consequences that must be weighted.

The eye fixation duration for the VMS remained on average below 1.4 s for all three VMS phases, which is still lower than the defined threshold of 1.6 s that can result in increased average response time to a hazard event (Horrey & Wickens, 2007). The GRIP displaying delay resulted in an average eye-fixation duration of 1.6 s and can, therefore, be considered as similarly effective for safe information intake while driving. Another research considers short glances of up to 2 s away from the forward roadway acceptable for scanning the driving environment (Klauer et al., 2006). The average eye-fixation durations for all GRIP messages were below 2 s, which indicates that the drivers were able to safely allocate their attention to the travel information displays and the freeway environment. Installing GRIPs on an overhead gantry in the central point of view appears to be beneficial to allow drivers to have their eyes still on the road (Reinolsmann et al., 2018). The drivers' visual attention depends on the demands of the driving environment, with drivers displaying longer mean fixation durations in low demand conditions when the sign is further away and in high demand conditions when the driver is close to the sign (Robbins et al., 2019). The drivers' eye-fixations before the first ATIS location resemble realistic driving conditions since the drivers were exposed to the newly updated travel information and had to be aware of the surrounding traffic. No speed variations were found between drivers, which indicates that drivers were still able to safely perform the driving task while looking at the travel information.

6. Conclusion and recommendations

It can be concluded that drivers' compliance with alternative route suggestions can be increased firstly, through contrasting delay time differences between the two routes and secondly, through highlighting the attractive travel attributes (i.e., drivers' gain) of the alternative route that is insufficiently captured by similar total travel times given the fact that detours are often distance-wise longer. Delay displays include indirect information about the travel conditions and real-time travel speeds, which helps drivers evaluate the performance of the alternative route. The GRIPs perform well in displaying congested or free-flow travel speeds through color-coding without negatively impacting drivers' attention to the roadway. However, color-coded GRIPs are not necessarily more effective than VMSs. Despite the past experience with VMS in Qatar, the study showed that other ATIS configurations (delay time displays and color-coding) do have a greater impact on drivers' route choice behavior than the default VMS displaying total travel times for two time-wise equal routes. Zero delay information appears to be also effective on a VMS despite withholding graphical information about the travel distance on the network. Although, a GRIP helps to improve the drivers' perceived travel time accuracy, it has been claimed that lower accuracy of drivers' perceived travel time can be associated with a better network performance (Li et al., 2016). It can be argued that VMS infrastructure, which is more prevalent than GRIP gantries, can be efficiently used to safely disseminate dynamic delay time information on freeways. The dynamic employment of delay times instead of default total times can help distribute traffic over the available road network through dynamically counteracting and balancing the increasing traffic intensity on two available freeway routes. It should be noted that the display of delay times should not be misleading since detours are characterized by longer travel distances. Therefore, it is important to change the display only to delay times once the total travel times for both routes are at least equal and, therefore, equally attractive to drivers. On balance, three policy recommendation can be made:

- It is recommended to switch from a travel time display to a delay time display to increase the percentage of drivers taking a time-wise equal detour. This strategy is most effective for VMS (36% to 74% taking the detour) followed by GRIP (61% to 81% taking the detour).
- If slower traffic occurs on the alternative route due to a temporary increase in traffic volume, road authorities are advised to activate phase 2 or 3 to accurately display delay times and warnings for both routes irrespective of the ATIS panel. In terms of display design, contrasting traffic information units and ATIS repetition can facilitate and influence drivers' decision making.
- It is recommended to determine in advance the available freeway network capacity and quality of the alternative route. Depending on the traffic management objectives, higher rerouting compliance of 25% can be expected for equal travel times being displayed on a GRIP as compared to the VMS.

Careful consideration should be taken when generalizing the results to other countries. Qatar represents a dynamically changing driving context where a lot of road infrastructure has been constructed and maintained during the past years. Besides, the large composition of international drivers and the cultural heterogeneity can influence the overall evaluation of the usefulness of freeway ATIS. Future studies with naturalistic traffic data are recommended to investigate the ATIS designs on route choices and driving behavior in larger driver samples. Also, an additional analysis of the changes in the detour route capacity is recommended to investigate the real-world effect of route choices on the network performance. Moreover, the characteristics of individual drivers can be further analyzed in follow-up analyses to predict the likelihood of diversion based on individual driver characteristics, which can be beneficial for in-vehicle display applications.

CRediT authorship contribution statement

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

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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