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From self-reports to observations: Unraveling digital billboard influence on drivers

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A R T I C L E I N F O

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A B S T R A C T

The objective of this current study was to evaluate the impact of digital billboards (DBs) on self-reported and observed driving behavior, given their established association with distracted driving. This investigation focused on driver behavior in Iran using a dual-pronged approach. Initially, self-reported driving behavior was analyzed using a Driving Behavior Questionnaire (DBQ), which was completed online by 453 drivers. The factor analysis of the questionnaire data emphasized the significant role of DBs in generating driving errors, lapses, unintentional violations, and intentional violations. The DBQ questions exhibited a clear factor structure, demonstrating high factor loadings and satisfactory internal stability. The findings indicated that advertising signages notably influenced drivers' behavior, particularly in instances of neglecting the behavior of the leading vehicle's driver (Lapse), disregarding pedestrian crossings (Error), disregarding red lights (Intentional violation), and overtaking without considering traffic flow behind (Unintentional violation). Subsequently, participants engaged in an Instrumented Vehicle Study (IVS) to explore observed driver behavior when encountering DBs (899 samples). Four factors were identified as significantly influencing the likelihood of driver distraction: the driver's crash history, time of day, driver's age, and road type. A logistic regression analysis was conducted using the IVS data, revealing that drivers with prior crash experience approached DBs with 8.8 times more caution than those without such a history. Moreover, young adults were 8.25 times more susceptible to distraction from DBs compared to their older counterparts. Notably, the findings suggested that drivers were nearly four times more prone to distraction at night compared to daytime. Additionally, drivers were twice as likely to be distracted at intersections compared to other road types. The outcomes of this study can offer insights for policy interventions regarding the content and placement of DBs, aiming to minimize their impact on road safety while still enabling advertisers to target their intended audience.

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1. Introduction

1.1. Overview of the impact of DBs on driving behavior

Under complex traffic conditions, drivers' insubordinate behavior may lead to crashes as a result of driver distraction. Relevant research conducted by the World Health Organization indicates that driver distraction is a growing threat to road safety (WHO, 2018). Overall, driver distraction occurs when drivers divert their attention from activities that are essential for safe driving towards other activities that may be irrelevant to driving.

Though there is an ongoing discussion in the literature regarding the most effective approach to defining driver inattention and distraction, two widely cited definitions exist. The first definition characterizes driver inattention as the "diversion of attention away from activities necessary for safe driving towards a competing activity, which may lead to a lack of attention or no attention to activities necessary for safe driving" (J.-Y. Lee et al., 2008). The second definition defines driver distraction as " Distraction involves a diversion of attention from driving, because the driver is temporarily focusing on an object, person, task or event not related to driving, which reduces the driver's awareness, decision-making ability, and/or performance, leading to an increased risk of corrective actions, near-crashes, or crashes" (Regan et al., 2009). Both of these definitions are conceptually valuable as they are based on the attention theory, which acknowledges the interconnected role of safety–critical and secondary (competing) activities.

A distracted driver temporarily splits their attention between the main task of driving and what is not directly related, such as talking on the cell phone. As a result of this process, the driver cannot devote their entire focus to the driving task. This is because most of their attention is spent thinking and concentrating on the phone conversation and not driving, which reduces their ability to drive well (Edquist et al., 2011). Factors affecting drivers' concentration levels, subsequently causing poor performance, can be categorized into two general categories; Internal and External. Internal factors affect a driver's performance while driving, such as by using a mobile phone, which reduces the driver's performance. Violations of the speed limit, red light violations, deviations from the road, or sudden changes in direction can all be caused by these factors (Dommes et al., 2015). External factors include a lack of attention by the driver due to vision limitations and/or the driver's gaze drifting due to a light source, such as advertising signages. There are three types of external distraction factors: 1) Situational clutter (all moving and fixed objects on the roadside), 2) Designed clutter (all traffic control devices), and 3) Built clutter (buildings, storefronts, and advertising digital billboards) (Belyusar et al., 2016; Edquist et al., 2011; Sheykhfard & Haghighi, 2020).

Regarding internal factors, the driver becomes less aware of traffic flow and less capable of controlling the vehicle while texting or talking on the phone, and such limited situational awareness can reduce the appropriate reaction time by 25 % (Acerra et al., 2019; Hoekstra-Atwood et al., 2019). Road crashes may result from lateral deviations of vehicles from the road line caused by distracted drivers or even pedestrians, especially those using cell phones (Farmer et al., 2015; Simons et al., 2008; Vlakveld et al., 2021). In general, a driver can be distracted by eating, drinking, talking to vehicle occupants, or listening to music, which constitutes different aspects of internal distraction and are all associated with an increased probability of a crash (Choudhary & Velaga, 2019; Fountas et al., 2019).

Besides, external factors emerge due to the development of technology and the importance of advertising in human societies, advertising signs, especially digital billboards, which are used more often than before. These devices can pose a greater risk to traffic safety than other external factors due to their attention-attracting nature (Plant et al., 2017). Drivers' behavior can be influenced by the presence of billboards on the roadside (especially digital billboards) in the short term (Anani, 2020; Mollu et al., 2018). However, digital devices are more likely to be able to influence driving behavior in the long term; in some studies, drivers have been observed to pay attention to digital billboards for up to two seconds (Beijer et al., 2004; Dukic et al., 2013). The time required for the driver to return to normal driving conditions after observing the billboards can be influenced by several factors, including the age and skill of the driver (Belyusar et al., 2016; Edquist et al., 2011). Some studies have also reported that the type of road, and even the size and text of billboards, can increase the duration of drivers' distraction (Crundall et al., 2012). Besides, distractions prevent the driver from fully focusing on the road, thus resulting in poor decision-making and driving performance (Kaber et al., 2015).

To reduce the frequency as well as the injury severity of crashes primarily caused by driver distraction, it is of utmost importance to identify the factors that cause distraction and implement appropriate measures to eliminate or significantly reduce their impact on road safety. Digital billboards (DBs) are among the external distraction factors affecting a driver's behavior to a more pronounced extent than others (Plant et al., 2017; Sheykhfard & Haghighi, 2020). The importance of these advertising signages for road safety draws from their inherent purpose to attract attention, and their excessive visual disturbance may reduce drivers' natural ability to cope with a potentially cognitively-demanding driving environment (Herrstedt et al., 2013; Oviedo-Trespalacios et al., 2019; Roberts et al., 2013). In fact, the distracting effects of the DBs may cause drivers to lose concentration while driving, resulting in poor driving performance, affecting the quality of the drivers' Perception Response Time (PRT), and impacting their ability to make appropriate decisions (Kaber et al., 2012; Roberts et al., 2013; Shaw et al., 2019). In summary, DBs have significant potential to compromise driving performance, as they: (i) directly affect the driving task and cause confusion, (ii) divert drivers' attention away from the driving task, (iii) trigger drivers' eyes to look off the road for a significant amount of time and, in turn, increase PRT, (iv) reduce drivers' lateral visibility, as they serve as a roadside obstacle, and (v) reduce drivers' attention to roadside warning signs (Roberts et al., 2013; Edquist et al., 2011; Young et al., 2007).

1.2. Previous research on DBs

Numerous studies have been conducted to investigate whether billboards can divert drivers' attention away from safety-critical driving tasks. The results of these studies have not been consistent, with some suggesting that billboards pose no safety concerns while others suggest otherwise. For example, Young et al. (2007) found that in certain situations where drivers needed to focus on immediate traffic or driving conditions, they were able to regulate their behavior around static billboards and remain focused on safety–critical driving tasks (Young et al., 2017). Similarly, Decker et al. (2015) reported no significant distraction effects from DBs as drivers could regulate their gaze behavior when driving demands changed (Decker et al., 2015). However, Gitelman et al. (2019) conducted a large-scale study in Israel and found that the removal of highway billboards was associated with a significant reduction of 30–40 % in injury-involving crashes, whereas the re-installation of the billboards resulted in a 40–50 % increase in the number of crashes (Gitelman et al., 2019).

According to a recent literature review by Oviedo-Trespalacios et al. (2019), roadside advertising has an impact on driver behavior, but the degree of impact may depend on both the characteristics of the driver and the advertising itself. Various simulator and on-road studies have examined the effects of billboards on driving performance. For instance, Young et al. (2007) found through the use of a driving simulator that the presence of advertisements on rural roads led to a fourfold increase in the amount of time vehicles were traveling outside designated lanes (Young & Mahfoud, 2007). This finding was corroborated by another small simulator study conducted by Bendak and Al-Saleh (2010).

Several studies have examined the effects of billboards on driving speed, but the results have been contradictory. Two simulator studies reported a decrease in average speed in the presence of billboards, while another simulator study and an on-road study found no significant impact on speed or speeding. The latter studies were conducted by Bendak and Al-Saleh (2010) and Lee et al. (2004). However, an on-road study conducted by Sisiopiku et al. (2015) found a significant increase in speed variation when billboards were present.

The effect of billboards on headway has been the subject of conflicting findings in the literature. While one simulator study found that participants drove significantly closer to the lead vehicle in the presence of billboards (Milloy & Caird, 2011), an on-road study found no relationship between billboards and headway (Smiley et al., 2005). These inconsistent results may be attributed to the examination of various types of billboards, under different circumstances, and among diverse drivers.

Studies have demonstrated that the presence of new objects in a person's visual field can distract their attention away from their main task and disrupt their intended eye movements by unintentionally diverting their eyes towards the object (Theeuwes & Burger, 1998). For instance, static billboards that are infrequently changed may be disregarded by drivers as they are familiar with the content (Wachtel, 2009). However, DBs may attract more attention due to their dynamic nature and distract drivers through dwell times and message transition times (Dukic et al., 2013).

A study by Meuleners et al. (2020) recently used a driving simulator study to investigate the effects of different dwell times on driving behavior for “simple” message displays. The study found that longer dwell times (60 s) did not negatively affect driving behavior compared to shorter dwell times (20 and 40 s). Another study by Mollu et al. (2018) examined eye glance behavior towards

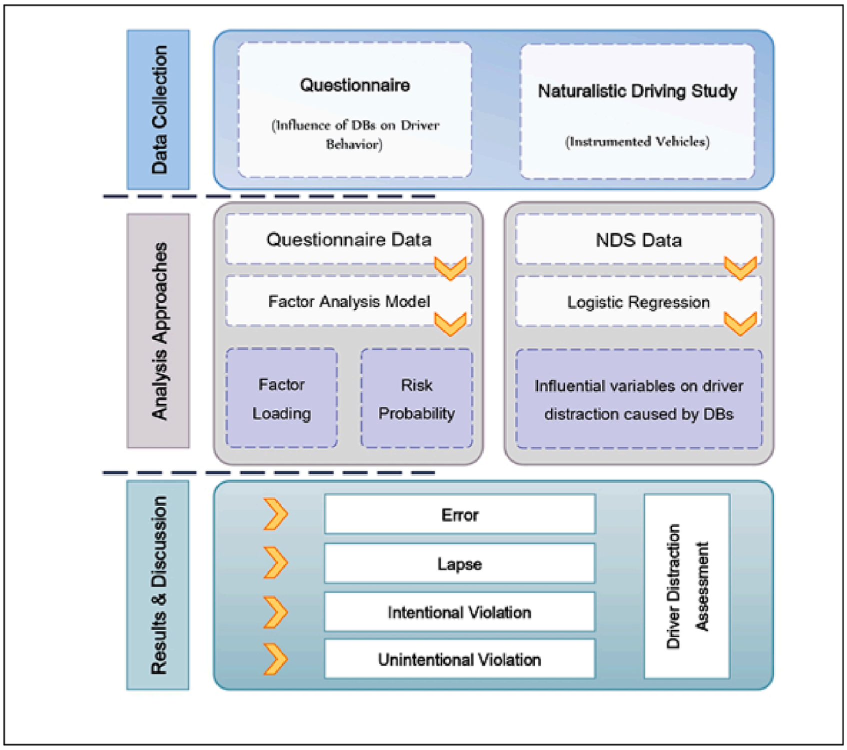

Fig. 1. The structure of the current study.

DBs around pedestrian crossings and found that the shortest dwell time (3 s) attracted the most eye glances but resulted in self-reported decrements in driving performance and increased mental workload.

Overall, the studies indicate that DBs can have negative effects on driving behavior by inducing distraction and visual discomfort, albeit the impact on driving performance is less clear. Some studies report negligible effects on driving performance, and others suggest that DBs can lead to longer reaction times and reduced peripheral detection performance. More extensive research is required to fully understand the effects of DBs on driver behavior and safety.

1.3. Research gap and research aims

The studies mentioned earlier had some limitations in terms of their methodologies or empirical settings. For example, some studies were conducted in driving simulators or laboratory settings, which may not accurately represent real-world driving conditions (Mollu et al., 2018; Sisiopiku et al., 2015; Thiffault & Bergeron, 2003; Vlakveld et al., 2021; Zangi et al., 2022). Additionally, some studies relied on historical data rather than collecting new data (Bendak & Al-Saleh, 2010; Decker et al., 2015; Sisiopiku et al., 2015; Sorum & Pal, 2022). As a result, the generalizability of the findings to real-world driving conditions may be limited. It is important to keep these limitations in mind when interpreting the results of these studies.

To date, there have been few studies that have investigated the role of advertising signages as a primary source of driver distraction. Additionally, there is limited research that has compared drivers' self-reported behaviors (perceived behavior) with their actual driving behaviors (observed behavior), particularly in relation to the impact of DBs on driver behavior. As a result, the current study aims to assess the self-reported data of drivers to explore the potential effects of DBs on driving behaviors, including violations, lapses, and errors, through the use of questionnaires. Lapses refer to minor attention or memory failures, or absent-minded behavior, which may be frustrating or have negative consequences for the driver responsible, but normally do not threaten anyone's safety (Lawton et al., 1997; Parker et al., 1995; Reason et al., 1990, Stephens & Groeger, 2009). Errors can be categorized as misjudgments or failures of observation with the potential for hazards or dangerous outcomes (Lawton et al., 1997; Parker et al., 1995; Reason et al., 1990). Violations are behaviors intended to harm and violate the law and are considered to be a form of sabotage (Reason et al., 1990). Furthermore, the study seeks to investigate factors that may contribute to distraction when drivers encounter DBs by conducting a naturalistic driving study (NDS) to identify these factors. The study utilizes a Structural Equation Model (SEM) to evaluate the relationships between these factors and determine the primary factors that influence driver behaviour, proposing an SEM model through factor analysis to describe the mechanism of how DBs impact driver behaviour. Fig. 1 shows the overall structure of the current study.

2. Material and methods

2.1. Ethi*****cs approval

The research involved human participants in both parts of the study (questionnaire and Instrumented Vehicle Study (IVS)) and received approval from the Human Research Ethics Committee at Babol Noshirvani University of Technology upon review of the research protocol. The committee ensured that the participants were protected throughout the study and that their data remained anonymous and confidential. The study recruited participants through a call for participation in the research study, which was launched by the Traffic Research Laboratory of Babol Noshirvani University of Technology in Iran and was disseminated through local newspapers and social media. To avoid participants' prior knowledge of the study's purpose and the presence of DBs influencing their actual driving behavior, those in the IVS study were not among those who filled out the questionnaires. However, the case studies considered in both the questionnaire and IVS data were in the same locations.

2.2. Case study

As a result of its natural attractions such as the ocean and forest, Mazandaran Province is one of the most popular tourist destinations in Iran. Therefore, millions of trips are made each year by domestic and foreign travelers. The particular geographical location of Babol City makes it a favorite destination for those wishing to travel to coastal or forest areas. Thus, it is quite common for DBs to be used to advertise recreational activities for travelers.

The present study is conducted in Babol County (with a population of 531,930), located in Mazandaran province (with a population of 3,073,943), Iran. According to the 2018 report of the Iranian Legal Medicine Organization, Mazandaran is one of the three provinces that reports the highest number of road crashes in the country. The report states that 647 deaths and 10,500 injuries were reported in 2021, of which, 50 % were associated with driving distractions (Iranian Legal Medicine Organization, 2022).

2.3. Questionnaire design

The questionnaire was designed in light of the Manchester DBQ, which consists of 13 items (Reason et al., 1990). An analysis of drivers' actions and faults was performed to design the present questionnaire considering four main groups of actions: lapses, errors, unintentional violations, and intentional violations. According to previous studies, the following definitions were used:

- Lapses: A driver may experience minor attentional or memory problems, or exhibit absent-minded behavior, which may frustrate or have negative consequences for the driver, but generally do not pose a threat to anyone's safety (Lawton et al., 1997; Parker et al., 1992; REASON et al., 1990; Stephens & Fitzharris, 2016).
- Errors: A misjudgment or failure of observation that may result in a hazardous or dangerous outcome (Lawton et al., 1997; Parker et al., 1992; Reason et al., 1990).
- Unintentional Violation: A behavior that leads to the violation of the law without the intention of doing so (Blockey & Hartley, 1995; Reason et al., 1990)Intentional Violations: A form of sabotage intended to harm and violate the law (Blockey & Hartley, 1995; Reason et al., 1990)
- Intentional Violations: A form of sabotage intended to harm and violate the law (Blockey & Hartley, 1995; Reason et al., 1990)

All items were measured using a six-point Likert scale, with the intention of capturing the frequency of a self-reported behavior (0 = never, 1 = rarely, 2 = occasionally, 3 = quite often, 4 = frequently, and 5 = almost all the time). Adaptations were made to the English questionnaire through back-translation when translating the Persian version. The translation of the items into Persian was completed by a native translator (fluent in Persian and English). There was no significant difference between the original and translated versions of the questionnaire. The questionnaire was also tested by different expert groups in both countries in order to check that the English version was compatible with the translated test items.

The questionnaire was administered online, and it took approximately 20 min on average to be completed. Through the online dissemination of the questionnaire, a generally balanced distribution of responses was obtained considering key demographics, such as gender and age. A total of 460 participants (Male: 53.4 %, Female: 46.6 %; Mean Age = 35.15; Range: 21 to 63 years old) completed the questionnaire voluntarily with no monetary incentive provided.

2.4. *Instrumented vehicle study (IVS)*

An Instrumented Vehicle Study (IVS) is a form of NDS that involves vehicles equipped with instruments that can collect real-time data about a driver's behavior and performance on the road. The data is collected through various sensors, cameras, and other measurement devices installed in the vehicle, and can be used to study driver behavior and identify factors that contribute to unsafe driving practices. IVS has been used in numerous studies (Ali & Ahmed, 2022; Boyce & Geller, 2002; Pantangi et al., 2019, 2020, 2021; Wali et al., 2018; Yarlagadda et al., 2021; Sarwar et al., 2017) to investigate the impact of different factors, such as distractions, fatigue, and alcohol, on driving behavior. It offers a unique opportunity to observe actual driving behavior in a natural setting, rather than relying on self-reported data or simulated scenarios.

The present study included 29 participants (15 males, 14 females; aged between 18 and 65 years old). The IVS study had a similar distribution of demographics as the questionnaire study. A total of 35 % of participants had less than three years of driving experience, while 65 % had more. The youngest (18–25) and oldest (over 55) drivers made up the smallest and largest groups (21 % and 39 %, respectively). The equipment used in the study consisted of a vehicle-mounted camera fitted into an instrumented vehicle, which recorded both the interior and exterior of the vehicle, as well as the interior audio. The camera's playback resolution was 640 × 480 DVD quality. An example of the camera recordings for a participant driving the instrumented vehicle is shown in Fig. 2. Participants drove the vehicle on a 35 km route in Babol County, which includes both urban and suburban roads with different characteristics and

Fig. 2. A participant driving the instrumented vehicle.

took about an hour to complete.

There were 31 DBs (17 in urban areas and 14 in suburban areas; 3.5 m * 4.5 m) in the predetermined routes. These DBs were comprised of P8 SMD Outdoor Street Advertising LED Displays, high-resolution outdoor LED screens designed for street advertising. With a pixel pitch of 8 mm and utilizing SMD LED technology for brightness, energy efficiency, and color consistency, these displays offer a pixel density of 15625dots/sqm and a brightness of ≥ 5000 cd/sqm. As a result, 899 samples (29participants*31DBs) were identified from the IVS study involving 29 participants, in order to assess the factors that contribute to drivers' distracted behavior.

2.4.1. Data coding and analysis

A team of four experts manually analyzed the videos that were drawn from the IVS at the Traffic Research Laboratory of the Babol Noshirvani University of Technology. They used a dedicated annotation toolbox developed with Microsoft Visual Studio 2019 to annotate the videos, which involved loading selected trips and playing them at their chosen speed. During the annotation process, the analysts received instructions and were assigned ten events to annotate, followed by a discussion to ensure everyone understood the variables to be drawn from the process. Each analyst was then assigned other events at random, and ten randomly selected events were used to assess their agreement.

Two statistical measures, Cohen's Kappa and the intra-class correlation coefficient (ICC), were employed to assess the agreement between annotators. Cohen's Kappa is used to evaluate the level of agreement between raters when categorizing items on a nominal or ordinal scale, considering chance agreement and providing a measure of agreement beyond chance alone (McHugh, 2012). The ICC, on the other hand, is used to assess agreement when multiple independent raters measure an outcome at a continuous level, evaluating variations between groups compared to variations within each group to explain total variance in the data (Koo & Li, 2016). A strong level of agreement among annotators was demonstrated by our analysis in SPSS, with a Cohen's Kappa value of 0.818 and an intra-class correlation coefficient value of 0.869, indicating robust consensus among annotators.

The entire annotation process took two weeks, and the resulting video recordings were analyzed to examine the driver's behavior and other variables of interest. The vehicle-mounted camera used to capture the videos also provided GPS map data, pinpointing the participant's exact location, as well as the vehicle's speed and rate of acceleration in G's. A summary of the variables of interest can be found in Table 1. The sampling rate for the time series data collected was 30 frames per second (fps). This frame rate was used to capture the temporal resolution of the data, including image and video recordings as well as other time-dependent variables.

2.5. Structural equation modeling (SEM)

SEM is a multivariate method for analyzing and evaluating causal multivariate relationships. This method comprises two statistical components: one that determines the structural relationship between latent variables (structural model) and one that specifies the relationship between observed and latent variables (measurement model) (Sheykhfard & Haghighi, 2020).

In this study, the SEM structure consists of four latent variables including Lapses, Errors, Unintentional violations, and Intentional violations, which are defined by their own observed variables. The SEM not only reveals the components of each latent variable but also uncovers the relationships between these latent variables and instances of driver distraction. Observed and latent variables are two fundamental concepts in statistical analysis, particularly when it comes to factor analysis and structural equation modeling. Latent variables, also known as exogenous variables, are those that are not directly measurable. Latent variables are therefore measured using observed measures or items that constitute the questionnaire's questions in the study.

2.5.0.1. Evaluation of the measurement model

The convergence validity of a measurement model constitutes a widely used evaluation criterion for examining the correlation

Table 1
Variables of interest in the IVS study.

Code	Variable	Description	Measurement unit / value
SPD	Speed	The speed of the vehicle	(KPH)
DST	Distance	The distance between vehicle and DBs	Meter
LIC	License	Time elapsed since the acquisition of driving license	Year(s)
D/N	Day or Night	Day or Night	Day: 1, Night: 0
EXP	Experience	Crash experience (if the driver has been involved in at least one crash in their lifetime)	Yes = 1, No = 0
D.AGE	Driver Age	Driver Age	Under 25 years = 1 25–35 years = 2 + 35 years = 3
D.GDR	Driver Gender	Driver Gender	Male = 1, Female = 0
R.T	Type of Road	Type of Road	Roundabout: 0 Intersection: 1 Other: 2
Distraction	Looking at DBs for minimum 2 s duration (away from the road) (Vlakveld & Helman, 2018; Wachtel, 2020)	Is driver distracted?	Yes:1, No: 0

between each factor and its indicators (Höck & Ringle, 2010). Specifically, the Average Variance Extracted (AVE) was used, which refers to the correlation between a factor and its items, and, as expected, the greater the correlation, the better the fit. An appropriate model should have an AVE greater than 0.5 (Chin & Quek, 1997; Höck & Ringle, 2010), which means that each factor (latent variable) must justify at least 50 % of their corresponding indicators' variances.

2.5.0.2. *Evaluation of the structural model*

Various criteria were employed to evaluate the fit of the structural model; the fundamental criterion used for the evaluation was the t-value (corresponding to the structural path coefficients). The t-value indicates a statistically significant association between the factors in the model, where a t-value greater than 1.96 indicates statistical significance at a greater than 95 % confidence level. As a point of emphasis, the values are only representative of the statistical significance of the relationship, not the actual strength of the relationship among factors. The influence of an exogenous factor on an endogenous factor was assessed using the R^2 value; according to the literature, three R^2 thresholds, specifically, 0.19, 0.33, and 0.67, corresponding to weak, moderate, and strong effects, respectively (Henseler & Chin, 2010).

The third index used for the structural model assessment is the Stone-Geisser Q^2 criterion, which measures the model's predictive power. This criterion, also known as the Q2 measure, is a widely used criterion for assessing the predictive ability or predictive validity of a latent variable model. The Q2 measure evaluates the model's ability to predict the observed values of endogenous variables (dependent variables) based on the latent factors or independent variables in the model. It is calculated by cross-validating the model against a holdout sample (Henseler & Chin, 2010). The model must be revised if the value of Q^2 for latent factors is less than or equal to zero, which may indicate that the relationships between the latent factors and other factors of the model are not well defined. Previous research has suggested cut-off values of the Q^2 criterion corresponding to different levels of prediction power; specifically, 0.02, 0.15, and 0.35, are cut-off values corresponding to weak, medium, and strong predictive power, respectively (Henseler & Chin, 2010).

2.5.0.3. *Overall evaluation of the model*

The Standardized Root Mean Square Residual (SRMR) and Normed Fit Index (NFI) were also used to evaluate the overall fit of the SEM model. NFI is a measure of the degree to which a statistical model fits the data without being influenced by the number of parameters or variables it contains (Hu & Bentler, 1998). In general, values greater than 0.8 indicate a practical fit between the model and the data. A structural equation model's root mean square error of approximation (RMSEA) is one of the most important indices used to assess the fit of the model; it is calculated by comparing the observed correlation matrix with the implicit correlation matrix of the model. The suitability of the model is indicated by values lower than 0.05 in most studies, although some studies report acceptable values lower than 0.08.

2.6. *Binary logistic regression*

In the present study, logistic regression models were developed to identify the factors influencing the possibility of driver distraction. In binary logistic regression, there are only two possible outcomes of the dependent variable (i.e., distraction vs no distraction). The explanatory variables indicate the factors affecting the probability that a driving distraction may occur when the vehicle encounters a DB. The logistic regression model is formulated as follows -

$$\Pr(Y_i = 1|x) = \frac{e^{logit(p)}}{1 + e^{logit(p)}} \tag{1}$$

$$logit(p) = \ln\left(\frac{p}{p-1}\right) = \alpha + \beta_1 \mathbf{X}_{1,i} + \beta_2 \mathbf{X}_{2,i} + \cdots + \beta_k \mathbf{X}_{k,i} \tag{2}$$

P (Y_i) is the probability of occurrence of driver distraction when the vehicle encounters a DB at the i^{th} interaction, $X_{k,i}$ denotes the independent variable *k* affecting the occurrence of a distraction for each interaction *i*, and β_k is the coefficient for each independent variable.

Before estimating the logistic regression model, Pearson and Chi-square tests were used to examine the correlation between the independent variables, with the results showing no evident correlation between the independent variables. Also, across all modeling stages, only the variables providing strong evidence of statistically significant impact on the dependent variable (p-value ≤ 0.05) were kept in the model; as such, all the independent variables included in the model specifications were statistically significant at a minimum 95 % level of confidence. The model providing the best statistical fit based on the collected data was estimated and presented in this paper.

3. Results and discussion

3.1. *Factor analysis and SEM results*

- *Correlation and Reliability*

A sampling adequacy test (KMO & Bartlett's test) was used to assess the suitability of the data for factor analysis. This test measures sampling adequacy for every variable in the model and the complete model, representing a measure of the variance proportion among variables that may be common variance. Factor analysis is more appropriate for data with lower proportions. KMO returns values in a range of 0 to 1. A value less than 0.6 indicates inadequacy of the sampling and unsuitability of the data for factor analysis, while a value greater than 0.6 indicates that there is a sufficient correlation between the data items to allow factor analysis to be conducted (Sarstedt & Mooi, 2014). As shown in Table 2, the mentioned test (KMO & Bartlett's test) was performed for the questionnaire sample. With KMO values of > 0.8, the sampling adequacy is considered to be satisfactory for the factor analysis. Cronbach's alpha coefficient is used to measure the reliability of factors derived from dichotomous (questions with binary outcomes) and multi-point scales. It takes values between 0 and 1, with a higher score indicating a higher level of reliability. In various studies, reliability coefficients of 0.7 have been found to be acceptable; however, in the relevant literature, there are also reports of lower thresholds (Ma et al., 2010). The values for Cronbach's alpha coefficients were calculated for the current study data (see Table 3**)**. Accordingly, the questionnaire data have good (high) reliability since the calculated coefficients for each of the principal components (i.e., each group of driving actions considered in the study) exceed the values recommended by the literature.

Table 4 exhibits the results of the questionnaire data analysis in the form of descriptive statistics (mean and standard deviation), factor loadings, and other indicators of the questions related to the components. Table 4 also shows the factor loadings of each question for each group of driving actions (component). The factor loading indicates the effect of each observed variable (question) on the latent variable (four principal components). Factor loadings take values in the range of 0 to 1, with values closer to 1 indicating stronger effects of the observed variable (question) on each of the latent variables (principal components).

According to different studies, factor loadings are divided into three classes of low, medium, and high impact, identified in the ranges of 0–0.5, 0.5–0.75, and 0.75–1, respectively (Lee et al., 2008). A weak factor loading indicates a low probability of impact, or in other words, relatively little influence of an observed variable on a latent variable. Also, factors with the moderate- and high-sized loadings indicate moderate and high influence of the observed variable on the latent variable. In Fig. 3, red and blue ellipses have been used to better represent questions with high and moderate factor loadings, respectively.

Based on Table 4, drivers reported in many cases that paying attention to DBs resulted in distraction from the direction of traffic flow. Consequently, they were unaware of the drivers' behavior in front of them (Q4; FL: 0.91). For this reason, they braked to avoid a crash with the vehicle ahead of them. Drivers who suddenly brake on a road without maintaining a safe distance from the vehicle in front are more likely to be involved in crashes. They may not realize that the vehicle in front of them is slowing down or coming to a stop, leading to a situation where the driver is traveling at a higher speed than the vehicle in front. This sudden braking can be a result of driver lapse, as the driver may not have been paying attention to the road and was caught off guard by the leading vehicle coming to a stop. Likewise, if the driver of the following vehicle does not maintain a safe distance or speed while suddenly braking on the road, they may cause a collision with the lead vehicle.

A driver's error can be attributed to three factors: failing to notice pedestrian crossings (Q11; FL: 0.95), failing to notice a vehicle approaching from behind (Q5; FL: 0.80), and deviating from the direct course (Q6; FL: 0.76). The questionnaire responses reveal reported instances where the drivers missed the marked pedestrian path due to their focus on the DBs. The misestimation of their distance to the pedestrian crossing was an outcome of the distraction caused by the DBs. Additionally, distracted drivers showed a tendency to deviate from a direct route while traveling, which can cause crashes when there is a high volume of traffic. Drivers have stated that an error can occur when the distraction makes them fail to pay attention to pedestrians in the area. When drivers are distracted by DBs, their attention may be focused on the billboard rather than the road ahead, making it more difficult for them to notice pedestrians in their vicinity. This can lead to accidents, particularly in areas with heavy pedestrian traffic. Also, they believe their attention may be diverted from their surroundings, including other vehicles on the road. As a result, they may fail to notice a vehicle approaching from behind, leading to a driving error. The latter can result in a collision or other unsafe driving behaviors. Moreover, distraction causes the drivers to suddenly realize that they have deviated from their intended path. This can occur when the driver's attention is focused on the DB rather than the road ahead. The driver may suddenly become aware of their deviation, and then perform sudden and unsafe maneuvers to correct their path. This sudden maneuvering can lead to accidents, particularly if other vehicles are present on the road.

One of the most important factors contributing to unintentional violations is the lack of attention to the flow direction before overtaking (Q10; FL: 0.89). Many drivers, without checking their mirrors for other vehicles behind them or on their sides, switch directions of their movement (especially at the start of the overtaking maneuver), which increases the likelihood of crashes, especially side-to-side crashes. It is important for drivers to avoid engaging in distracting behaviors while driving to reduce the risk of unintentional violations. When drivers encounter DBs, they may be more likely to overtake the vehicle in front of them before checking their side mirror because their attention is not fully focused on the road and traffic conditions and they may not be aware of the presence of other vehicles in their proximity.

Intentional violations can also occur when a driver takes actions to deliberately disregard traffic laws or regulations. Drivers are classified as intentional violators of traffic law when they engage in aggressive driving behaviors, such as honking or flashing their lights to overtake the vehicle in front (Q3; FL: 0.82). Distraction may cause the drivers to intentionally use their horns or flash their

Table 2
Sampling adequacy test and questionnaire reliability.

KMO Test	Bartlett's Test		
	Chi-square	df.	Sig.
0.792	138.295	78	0.416

Table 3
Questionnaire reliability.

1st component (lapse)	2nd component (errors)	3rd component (unintentional violations)	4th component (intentional violations)
0.88	0.89	0.83	0.91

Table 4
Factor analysis results.

Component	Question No. (Item)	Avg.	Std.	Factor Loading (FL)	t-stat
Lapses	4. Due to the distraction caused by the DBs, you did not notice the decrease in the speed of the vehicle in front, so you have to brake to avoid crashes with it.	1.43	0.62	0.91	3.51
	7. The effect of DBs on your behavior has made you forget what gear you are driving, so you have to check it.	0.61	0.84	0.65	2.12
	8. You have decided to go to destination A, but you suddenly realize that you are on the way to destination B due to being distracted.	0.52	0.82	0.61	2.75
	12. Due to the distraction caused by DBs, you did not pay attention to the person who suddenly appeared from behind a bus or a parked vehicle, and it was too late to brake.	0.86	0.54	0.69	4.69
Errors	5. Due to the distraction caused by DBs, you did not notice a vehicle approaching from behind.	0.99	1.36	0.80	3.85
	6. Due to the distraction caused by DBs, you suddenly realized that you had deviated a bit from your path.	1.48	1.19	0.76	3.19
	11. Due to the distraction caused by DBs, you did not pay attention to the presence of pedestrians in the area.	1.48	0.76	0.95	2.68
Unintentional violations	1. The presence of DBs makes you forget to look at the speedometer.	0.55	0.76	0.63	1.99
	10. Engaging in DBs has caused you to overtake the vehicle in front before checking your side mirror to overtake.	1.55	0.82	0.89	3.98
	13. You have not seen the road signs and driving directions because of DBs.	0.46	0.75	0.72	3.72
Intentional violations	2. Because of seeing a certain advertisement, you tend to increase your speed, so you get bored with the driver who drives slowly and overtake him.	0.88	0.87	0.64	4.15
	3. In order to pass the DBs location, to prevent its possible effect on your performance, you flash the light/horn to the front driver to get out of your way.	0.65	0.97	0.82	2.92
	9. The effect of DBs has caused you to cross the red light that has just turned red.	1.22	1.65	0.90	3.08

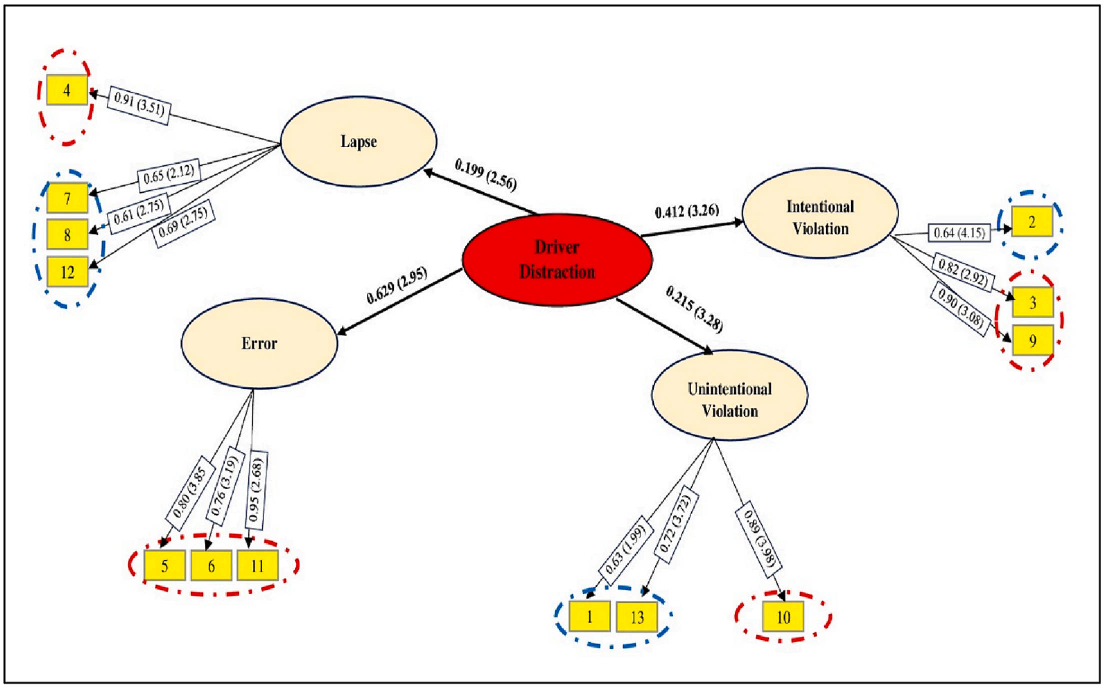

Fig. 3. Diagram of structural equation model of components driving behavior with distraction.

lights to pressure the drivers in front of them to move out of the way. This type of behavior not only sets the driver and other users on the road at risk but also violates traffic laws and regulations regarding the proper use of vehicle equipment, such as horns and lights. The questionnaire data shows that some drivers increased their speed in the presence of DBs and put pressure on the driver of the leading vehicle to allow them to overtake by honking repeatedly. Rear-end collisions are likely to occur if the vehicle in front fails to respond properly in a timely manner. In addition to aggressive driving behaviors, several drivers who participated in the questionnaire mentioned that the light reflection caused by the DBs at night prompted them to cross red lights that had just turned red (Q9; FL: 0.90).

This research also aims to highlight the effect of DBs on driving behavior in terms of inducing distraction. Fig. 3 provides a comprehensive illustration of the structural equation model, which does not only show the items composing each of the latent variables but also the identified relationships of the latent variables with the occurrence of driver's distraction. Behaviors such as lapses, errors, and violations have direct impacts (positive factor loading coefficients) on distraction occurrence. Smaller factor loading coefficients indicate that the factors have lower effects on distraction. Accordingly, lapse (FL: 0.215) and unintentional violations (FL: 0.199) contributed less to the occurrence of distraction, whereas error (FL: 0.629) had the most significant factor associated with the occurrence of driver's distraction. In this regard, the role of intentional violations (FL: 0.412) was also significant, but less pronounced than that of the error. Hence, it seems that the effect of DBs on driver behavior is translated into the emergence of driving errors and intentional violations.

Billboards on the side of the road are intended to attract the driver's attention, which is then diverted from traffic conditions, potentially resulting in more traffic crashes (Belyusar et al., 2016; Dukic et al., 2013; Edquist et al., 2011). Numerous studies have shown that roadside advertising signage can influence driving behavior (Beijer et al., 2004; Crundall et al., 2012; Regan et al., 2009). Furthermore, drivers are attracted to billboards by their visual appeal, which causes a delay in reaction time and increases their risk of making errors, especially when drivers face unanticipated conditions on the road (Beijer et al., 2004; Crundall et al., 2012). While the present study confirmed the effect of DBs on driver distraction, it also demonstrated how this issue can impact different components of driving behavior. In this study, the results showed that driving errors and violations are the most serious consequences of driver distraction. As a result of these two components, crashes may occur even more under complex traffic conditions. A large body of previous studies have reported the impact of components, such as driving error, on the occurrence of accidents (Kontogiannis et al., 2002; Koppel et al., 2017; Lucidi et al., 2010).

Taking into account the findings of the current research regarding the relationship between distraction and the occurrence of driving violations and errors, it is recommended that more comprehensive studies be conducted in the future, above all regarding the negative effects of advertising signages on driving behavior. The findings of such studies can potentially inform the development of traffic rules, which are indeed required to rationalize the use of DBs on the road, without compromising the level of driver safety.

3.2. Evaluation of SEM

The evaluation of the final model was conducted upon a thorough review of the measurement and structural models, as well as an evaluation of the overall performance of the SEM in terms of statistical fit.

The measurement model evaluation in Table 5 shows that all latent variables have an average value of greater than 0.5, indicating good convergent validity. The structural model analysis revealed significant relationships among the latent variables at a 95 % confidence level. The R2 value of 0.712 suggests strong effects of exogenous factors on the dependent variable, while the Q2 value of 0.38 demonstrates adequate prediction of the dependent variable by the independent factors. In the overall evaluation, the NFI and SRMS criteria yielded values of 0.912 and 0.030, respectively, indicating a good fit for the final estimated models in the study.

3.3. Binary logistic regression model of observed distraction

The probability of driver distraction due to the influence of DBs was investigated through the logistic regression method. The model's dependent variable indicates distraction ($Y = 1$) or a lack of distraction ($Y = 0$; i.e., the driver continued with the previous driving style). As a first step, non-significant variables were identified by the t-statistic values corresponding to their coefficients. After determining these variables (t-statistic values greater than 0.05 as we considered a minimum 95 % confidence level for statistical significance), they were eliminated from the original model, and the estimation process resumed with the remaining variables. Correlations between continuous and discrete variables were also examined through Pearson correlation coefficients and Chi-square tests. The results indicated that there was no significant correlation between the independent variables in the model.

Among the eight variables defined in Table 1, four of them significantly affected the probability of driver distraction, namely driver's experience (EXP), time of the day (D/N), driver's age (D.AGE), and type of road (R.T). Table 6 provides the results of the binary

Table 5
Evaluation of the measurement model.

Latent Variable	Convergent Validity	
	AVE	>0.5
Errors	0.592	✓
Lapse	0.528	✓
Intentional Violations	0.539	✓
Unintentional Violations	0.621	✓

Table 6
Estimation Results of the Logistic Regression Model on Driver Distraction.

Variable		Coefficient	p-value	Std. error	t-stat
Constant		−0.022	−0.630	0.033	−2.258
EXP	Yes	− 2.190	0.015	0.035	−3.125
D.AGE	Under 25 y.o.	+2.125	0.011	0.019	3.261
D/N	Night	+1.596	0.029	0.025	2.410
R.T	Intersection	+0.726	0.001	0.021	2.135
Likelihood Ratio Test		−2 Log-Likelihood: (Intercept only)		113.952	
		−2 Log-Likelihood: (Final)		98.146	
		Sig		0.016	
		Degrees of freedom (df)		14	
Goodness-of-Fit		Pearson (Chi-Square)		87.528	
		Sig		0.919	

logistic regression model that explores the determinants of driver distraction. The magnitude of a variable's βi coefficient, irrespective of its sign, indicates the magnitude of influence of the associated independent variable on the target variable, i.e., the probability of distraction.

Notably, the driver's experience emerged as the most significant factor, which was found to decrease the likelihood of distraction. The results revealed that drivers who had previously been involved in an accident(s) were 8.8 times more cautious in dealing with DBs while driving than their counterparts with no such accident history (odd = $e^{2.190} = 8.8$). Consequently, their probability of distraction was significantly lower. Drivers who have been involved in previous accidents tended to acknowledge and react to apparent driving risks compared to those who have not, leading to increased vigilance while driving. Their heightened awareness can reduce their susceptibility to external distractions, such as DBS, which require drivers to shift their attention away from the road. Studies have shown that drivers with prior accident experience are more likely to maintain a constant speed and lane position while driving past DBs, suggesting that they are less likely to be distracted by such stimuli (Gitelman et al., 2019).

Conversely, drivers younger than 25 years old showed a positive correlation with the likelihood of distraction. The regression analysis indicated that young adults were 8.25 times more prone to distraction by DBs than their older counterparts (odd = $e^{2.125}$ = 8.25). Young adults are more prone to distraction by DBs while driving compared to older age groups due to several factors, including weaker attentional control, higher risk-taking tendencies, lack of experience in dealing with cognitively demanding driving tasks, and the attention-grabbing nature of these advertisements. Young adults have been found to have relatively lower levels of attentional control compared to older adults, making them more vulnerable to the attention-grabbing effects of DBs. Additionally, many DBs feature content that is specifically targeted toward the younger population, including advertisements for entertainment, technology, sports, and fashion products. These types of advertisements are often designed to be visually engaging and exciting, which may be particularly attractive to young adults. Also, young adults are often more prone to taking risks, further increasing their susceptibility to distraction from DBs.

The time of the day and road type were also found to increase the probability of driver distraction. Specifically, the findings demonstrated that drivers were 4.88 times more susceptible to distraction at night than during daylight (odd = $e^{1.596} = 4.88$). Driving at night can significantly increase the risk of distracted driving due to reduced visibility, low ambient lighting, and driver fatigue. DBS can add to this risk through their eye-catching nature that can easily draw drivers' attention away from the road; external stimuli that interact with the visual field of the driver can induce distracting effects, especially when the ambient lighting is limited (Fountas et al., 2020). Studies have found that drivers are more likely to be distracted by DBs at night than during the day, and this distraction can lead to longer response times and a greater risk of accidents (Sheykhfard & Haghighi, 2020). Besides, the brightness and dynamic visual content of DBs can be particularly distracting for drivers in low light conditions, such as those encountered at night. As drivers gaze at DBs, they may become cognitively absorbed by the content, leading them to divert their attention from the driving task. This cognitive distraction can increase the driver's response time and reduce their ability to perceive and react to potential hazards on the road. Furthermore, the bright light emitted by DBs can create glare that can further reduce the driver's visibility and increase their level of discomfort or fatigue, further compounding the risk of distracted driving at night.

Moreover, drivers were twice as prone to distraction at intersections as on other types of roads (odd = $e^{0.726} = 2.08$). In urban areas, DBs have become a common sight, but there are growing concerns about their potential to distract drivers. Intersections are locations where the probability of distraction by DBs is particularly high compared to other types of roads. The high level of visual and cognitive demands placed on drivers at intersections, including monitoring traffic signals, observing other vehicles and pedestrians, and making safe decisions, can overwhelm the attentional resources of the driver, leaving them less able to filter out non-anticipated external distractions, such as DBs. Furthermore, DBs are often strategically placed at intersections, where drivers are more likely to be traveling at slower speeds or stopping due to traffic signals. In turn, this causes the drivers to have more opportunities to view the advertisements, increasing the likelihood of distraction.

4. Discussion

Table 4 provides the self-reported causes of drivers' behaviors distracted by DBs, including violations, lapses, and errors, as drawn by the questionnaire responses. The results indicate that when drivers are distracted by DBs, their attention is diverted from the road ahead, making it more difficult for them to notice changes in traffic flow. As a result, they may not realize that the vehicle in front of them is slowing down or coming to a stop, leading to a situation where the driver is traveling at a higher speed than the vehicle in front. In such a case, the driver is subject to abrupt braking to avoid a rear-end collision with the leading vehicle. This braking behavior of the driver can be considered as a result of lapse, as the driver may not have been paying attention to the road and was caught off guard by the vehicle in front coming to a stop.

Regarding the effect of DBs' distraction on drivers' errors, three factors hold the most significant impact. First, drivers have stated that an error can occur when the distraction makes them fail to pay attention to pedestrians in the area. When drivers are distracted by DBs, their attention may be focused on the billboard rather than the road ahead, making it more difficult for them to notice pedestrians in their vicinity. This can lead to accidents (with or without pedestrian involvement), particularly in areas with heavy pedestrian traffic. Also, their attention may be diverted from their surroundings, including other vehicles on the road. As a result, they may fail to notice a vehicle approaching from behind, leading to driver error. This error can result in a collision or other unsafe driving behaviors. Moreover, distraction causes drivers to suddenly realize that they have deviated from their intended path (e.g., deviating from lane boundaries). This can occur when the driver's attention is focused on the DB rather than the road ahead. The driver may suddenly become aware of their deviation, leading to sudden and unsafe maneuvers to correct their path. This sudden maneuvering can lead to accidents, particularly if other vehicles are present on the road.

The SEM analysis highlighted drivers' intentions of avoiding engaging in distracting behaviors during the driving task as a means to reduce the possibility of unintentional violations. However, a considerable number of drivers supported that distraction by DBs makes them not realize changes in the traffic signal display while they are driving, and, as such, they inadvertently run a red light. Drivers think that when they encounter DBs they may be more likely to overtake the vehicle in front of them before checking their side mirror because their attention is not fully focused on the road and traffic conditions, and as such, they may not be aware of the proximity of other vehicles. Intentional violations can also occur when a driver takes actions to deliberately disregard traffic laws or regulations.. In addition, distraction may cause the drivers to intentionally use their horns or flash their lights to put pressure on the drivers of leading vehicles to move out of the way. This type of behavior not only poses risks to the driver and other users on the road but also constitutes a clear violation of traffic laws and regulations regarding the proper use of vehicle equipment, such as horns and lights.

As to the observed driver distraction, the advancements and novel insights gained by our research are presented through a comparison of our findings with the results reported in previous studies, thereby providing a comprehensive understanding of the subject.

- *Previous accident experience and perception of driving risk*: The results show that drivers who have been involved in at least one accident in the past are less likely to get distracted by DBs compared to those with no accident history (as shown by the negative coefficient of the variable EXP in Table 6). This aligns with previous research that suggests drivers with prior accident experience tend to exhibit increased vigilance while driving (Alberti et al., 2014; Thiffault & Bergeron, 2003; Zangi et al., 2022), above all for younger drivers (O'Brien et al., 2017) who tend to exhibit less risky and more cautious driving style upon the accident event. The notion of increased awareness leading to more cautious reactions to distractions, such as DBs, is supported by earlier studies as well. However, any changes in the driving behavior in the post-crash period may be subject to the driving experience or cognitive mechanism of the driver (Terum and Svartdal, 2019) or temporal effects (O'Brien et al., 2017), so this association is suggested to be further investigated in the future.
- *Susceptibility of young adults to distraction by digital billboards*: The results highlight that young adults are more susceptible to distraction by DBs while driving compared to older age groups (as shown by the positive coefficient of the variable D.AGE in Table 6). This susceptibility is attributed to factors such as weaker attentional control, higher risk-taking tendencies, and the attention-grabbing nature of the advertisements. These findings are consistent with previous studies that have also identified young adults as a vulnerable group due to their reduced attentional control and affinity for visually engaging content (Edquist et al., 2011; Stavrinos et al., 2016).
- *Increased risk of distracted driving at night*: The results suggest that driving at night can significantly increase the risk of distracted driving, with DBs exacerbating this risk. Previous research supports these findings, indicating that drivers are more likely to be distracted by DBs at night compared to daytime (as shown by the positive coefficient of the variable D/N in Table 6). This finding is line with previous evidence (Decker et al., 2015; Oviedo-Trespalacios et al., 2019; Sheykhfard & Haghighi, 2020). Factors such as reduced visibility, driver fatigue, and the cognitive distraction caused by the bright and dynamic content of DBs contribute to longer response times and a greater risk of accidents.
- *Distraction by digital billboards at intersections*: The results highlight intersections as locations where the probability of distraction by DBs is particularly high. In fact, the positive coefficient of the variable R.T. (see Table 6) indicates that drivers at intersections are more likely to get distracted by DBs. This finding aligns with previous studies that have identified intersections as contexts with high visual and cognitive demands on drivers (Lemonnier et al., 2020; Patoine et al., 2021). The need to monitor traffic signals, observe other vehicles and pedestrians, and make safe decisions can tax a driver's attentional resources, making them more susceptible to distractions such as DBs, which are often strategically placed at intersections.

4.1. Policy implications and conclusions

This study investigated the behavior of drivers encountering roadside DBs in Babol City, Mazandaran province, Iran, through two different approaches targeting self-reported and observed driving behavior. In the context of the first approach, the self-reported driver distraction was addressed via a questionnaire-based study, which enabled eliciting information about the perceived behavior of 453 drivers from different socio-demographic backgrounds. Specifically, 13 questions were deliberately included in the questionnaire to ascertain the extent of perceived distraction of drivers when facing DBs. The self-reported data were extracted through an online questionnaire and were analyzed using an SEM approach. The findings of the data analysis indicate that DBs have a significant impact on the behavior of drivers, leading to lapses, errors, and intentional and unintentional violations. Among the possible distraction-related lapses, not paying attention to the behavior of a leading vehicle had the greatest impact. Additionally, not paying attention to pedestrian crossings was recognized as the most critical distraction factor that leads to errors. Overtaking without paying attention to the traffic flow behind (unintentional violation) and running a red light (intentional violation) were identified as key nuances of the effect DBs had on driving behavior.

In the context of the second approach, we investigated the observed effect of DBs on driver distraction through the collection and analysis of IVS data. The use of naturalistic information, such as that gained by the IVS, can better articulate the role of demographic and driving characteristics, including age, experience, time of day, and road type, without dealing with the bias that is typically induced by self-reported data. Participants drove an instrumented vehicle equipped with a mounted camera that recorded both the inside and outside of the vehicle. Logistic regression was used to determine the probability of distraction due to the influence of DBs. Four out of eight variables that were drawn from the IVS significantly affected the probability of driver distraction, including the driver's experience, time of day, driver's age, and type of road. Driver experience emerged as the most significant factor that decreased the likelihood of distraction, while drivers aged below 25 years showed a positive correlation with the likelihood of distraction. The time of day (night) and road type (intersection) also increased the probability of driver distraction. The results revealed that drivers who had previously been involved in an accident were 8.8 times more cautious in handling DBs than their counterparts with no such record, and their probability of distraction was significantly lower. Drivers who have been involved in previous accidents tend to perceive driving as a more risky activity compared to those who have not, leading to increased vigilance while driving. On the other hand, young adults were 8.25 times more prone to distraction by DBs than their older counterparts due to weaker attentional control, higher risk-taking tendencies, and the attention-grabbing nature of these advertisements. The time of day also played a significant role, with drivers being 4.88 times more susceptible to distraction at night than during the daylight, leading to increased risk due to reduced visibility and driver fatigue. DBs can further exacerbate this risk by diverting the drivers' attention away from the road. Furthermore, drivers were twice as prone to distraction at intersections than on other types of roads.

The results of this research can be useful to policymakers in several ways. Firstly, the study findings can provide them with a better understanding of the impact of DBs on driver behavior and the factors that contribute to driver distraction in the presence of such billboards. This knowledge can inform the development of regulations and guidelines aimed at minimizing the negative effects of DBs on road safety. These guidelines could be related to the operational hours of DBs (e.g., limiting their operation during peak hours), their content (e.g., avoidance of highly dynamic content and preference towards static content), and their brightness and contrast, especially during the nighttime. Secondly, this study can help policymakers identify areas for further research and data collection, such as examining the effectiveness of different types of DB displays (e.g., static, full-motion, 3D, augmented reality DBs, and so on) and how they impact driver behavior. This can inform future policy decisions related to DB regulations and their placement. Lastly, the study can assist decision-makers and local authorities in making informed decisions about the appropriate locations for DBs based on the findings related to driver behavior and distraction. This can help ensure that DBs are placed in areas and at safe minimum distances from the road boundaries to minimize their negative impact on road safety, while still allowing advertisers to reach their intended audience. Overall, the study can provide policymakers with valuable insights into the potential impact of DBs on driver behavior, which can inform their decision-making process when developing policies and regulations related to road safety and advertising.

In conclusion, this study highlights the impact of DBs on driver distraction and the importance of considering demographic and driving characteristics when investigating distraction-related issues. The findings suggest that driver experience, age, time of day, and road type are major determinants of driver distraction in the proximity of DBs. However, this study is not without limitations. There are several limitations to the questionnaire-based studies, which make them less than ideal sources of comprehensive and reliable information. Consequently, future extensions of this study might explore in more detail the impact of drivers' cognitive characteristics on the occurrence of road crashes, including medical and behavioral-cognitive skills evaluation along with psychological assessments, using non-invasive technologies (e.g., EEG) and driving simulations. Additionally, to develop more robust and universal behavioral models, it is recommended that future studies include larger and more representative samples of the drivers' population since this will allow researchers to meticulously analyze variations in driving behavior influenced by key socio-demographic factors, such as age, gender, or ethnic background. Other limitation of the study was the absence of incentives for participants, potentially contributing to a self-selection bias. The decision not to offer incentives was primarily due to budgetary constraints, resulting in a participant pool composed of individuals who may have been particularly interested in the research topic, potentially leading to a lack of diversity in the sample. As a result, the generalizability of the findings may be affected, and the study may not fully capture the perspectives of a broader population. In future research endeavors, addressing this limitation by exploring options for providing incentives, such as non-monetary rewards or participation in related events, will be crucial to encouraging broader participation and mitigating potential biases in participant selection. While this study delves into the perceived and observed impact of DBs on driving behavior, there are still gaps in the current state-of-knowledge, which could not be addressed by the specific research. These gaps are associated with the impact of DBs on reaction times and peripheral detection, which are also important for driver performance, as stated in an earlier section. Future research could provide new insights into these cognitive workload aspects by collecting more advanced naturalistic information enriched with eye-tracking data. Furthermore, future research could also draw more granular information on the extent of crash and driving experience of drivers to establish more robust relationships between these factors and the distraction proneness.

Finally, it is important to acknowledge that although driving behavior is a very complex aspect of human behavior and no method is capable of addressing all its nuanced complexities, research methods that enhance our current understanding of the causes and consequences of different driving aberrant behaviors can still be very helpful.

CRediT authorship contribution statement

Abbas Sheykhfard: Data curation, Formal analysis, Investigation, Methodology, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Mohammad Azmoodeh:** Data curation, Formal analysis, Investigation, Visualization, Writing – original draft, Writing – review & editing. **Boniphace Kutela:** Formal analysis, Writing – original draft, Writing – review & editing. **Subasish Das:** Formal analysis, Writing – original draft, Writing – review & editing. **Grigorios Fountas:** Formal analysis, Writing – original draft, 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.

Data availability

Data will be made available on request.

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