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Research Article

# Evaluation of the lateral acceleration on highway comfort: A case study with university students

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## ABSTRACT

Highway geometric standards are defined depending on the road users –both passengers and drivers- and vehicle characteristics, as well as the land structure on which the route is located. The limit values for the radius of the horizontal curves, the maximum flow rate, and the combination of the curve characteristics are calculated according to the safety and comfort parameters. As the comfort parameter, lateral acceleration acting on the passenger while traveling on a curved section or the change of this lateral acceleration in unit time is used. In the current situation, the limit value of the lateral acceleration used in Turkey is 1.47 m/s2 [1]. However, it is not known if this value is still suitable considering the technology enhancements and the changes in people's expectations. The limit value of lateral acceleration brings out negative economic consequences for both the users and constructers when it is lower than necessary. Too safe standards force constructers to increase the radii of the curves which increases the construction costs or creates a need for speed limitation which increases the fuel costs via braking and accelerating. This study aims to evaluate the suitability of the existing limit value with a case study involving test drives and a survey. During the test drives different levels of lateral acceleration geometrically permissible within the vehicle are produced and the level of perception of this lateral acceleration is determined. Within the scope of the project, the case study is done with university students. In the survey, participants are asked to answer demographical questions and rate their level of comfort perception. The perception levels are considered in five different categories according to the level of discomfort. Data such as age, vehicle ownership, gender, weight, height, and transportation mode choices for their regular trips were also taken from the participants and the relationship between these and comfort perception was investigated. The results obtained from this study were investigated to determine whether it is necessary to disseminate the study to a broader group and whether the limit value is suitable for the age group we studied with. The results of this study, which will contribute to the literature in terms of evaluating this common standard, showed that the lateral acceleration limit value is lower than necessary and an advanced study with larger groups may suggest changing the standard.

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## INTRODUCTION

Highway geometric standards are defined depending on the road users and vehicle characteristics, and the land structure on which the route is located [2]. Limit values regarding the horizontal curve radius, maximum superelevation, and combination curve properties are calculated according to road users' safety and comfort parameters. The lateral acceleration or the rate of change of the lateral acceleration per unit time, which is a jerk, in the horizontal curve is used as the comfort parameter.

The acceptable limit value of the lateral acceleration, which constitutes the comfort parameter for horizontal curves, depends on the road users' perception in the vehicle, but may vary for different countries and different vehicle types. Currently, 1.47 $m/s^2$ is used as the limit value of the lateral acceleration in Turkey [1]. However, it is not known if this value is suitable for Turkey in road design or how the perception of comfort has evolved since the determination of this value in 1991 by The American Association of State Highway and Transportation Officials (AASHTO), especially in university students [2]. The materials and methods we used in our study, which we conducted to shed light on this unknown, offer a different measuring instrument than those in similar studies and an opportunity to measure comfort perception.

Our study aims to produce the geometrically maximum permitted lateral acceleration and to determine the comfort perception level with this lateral acceleration in the vehicle with different parameters. Test rides were carried out with 10 male and 10 female participants during the fieldwork. Participants were asked to answer the demographical questions regarding their age, vehicle ownership, gender, weight, height, and the transportation mode they regularly use before test rides. The survey sheet included the plan for the test ride route, and participants are asked to fill out their level of comfort at the center of each curve numbered in the plan of the route on the survey sheet. Perception levels have been handled in 5 different categories in Likert scale, depending on whether the lateral acceleration is not felt at all or can be felt at the level of discomfort. The relationship between the demographical data of the participants and their perception of comfort was investigated.

The purpose of this study is to reveal the relationship between the geometric standards applied while designing the highway structures and the comfort perception created by the lateral acceleration. For this purpose, a piece of equipment has been designed for the measurement of lateral acceleration, measuring the horizontal curve position and the lateral acceleration occurring at any point within the horizontal curve. The reactions of university students, the comfort perception corresponding to the particular lateral acceleration values, were measured.

The paper is organized as follows. In the next section, the literature review is presented. Following that, the materials and methods of the study are described. In the fourth chapter, the evaluation and analysis of the collected data are given. And finally, we share our results, and discussions and recommendations for further studies.

## BACKGROUND

When it comes to the geometric standards of a highway, limit values for platform width (lane and shoulder width), minimum horizontal and vertical curve radii, maximum longitudinal and transverse slopes, roof slope, bridge width, minimum underpass height, expropriation width are understood [3].

The choice of geometric standards is essentially a matter of need and cost. For example, if there is a situation to pass a high volume of traffic quickly and comfortably, it is desired that the road standards are high. Besides, it is an important issue that the road standards meet the promised level of service throughout the project life.

Vehicles moving in a superelevated horizontal curve on a road section are subject to a lateral acceleration caused by the centrifugal force. F' force that causes the lateral acceleration is seen in Figure 1.

Two forces, the centrifugal force and the components of the vehicle weight, are effective in the emergence of the F' force. The first is the coupling of centrifugal force parallel to the superelevated road surface (F.cosα); the second is the component (Q.sinα) of the vehicle weight parallel to the superelevated road surface in the direction of the center of

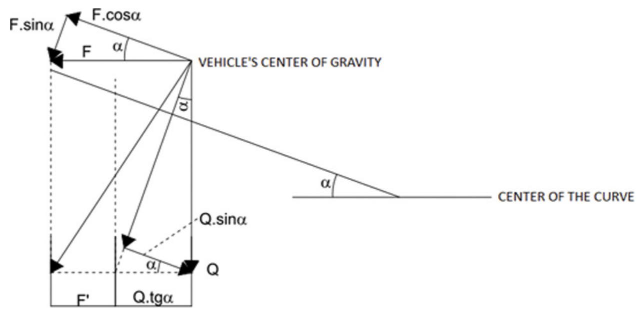


**Figure 1.** The F' force that generates the transverse acceleration.

the curve. The equivalent of this force is (Q.tgα) horizontally. While normally, this force is expected to meet the centrifugal force, an unbalanced part occurs, as seen in Figure 1. Here, the force that causes the lateral acceleration is this unbalanced component that is formulated as follows.

$$F = \mathrm{F} - \mathrm{Q.tg}\alpha \qquad (1)$$

In this equation, where p is the lateral acceleration, if the terms of force and weight are expressed in terms of vehicle mass,

$$\mathrm{m.p} = \mathrm{m}.\frac{\mathrm{v}^2}{\mathrm{R}} - \mathrm{m.g.ta}\alpha \qquad (2)$$

is obtained.

In Equation 2,

p: lateral acceleration ($m/s^2$)

m: the mass of the vehicle (kg)

v: velocity of the vehicle (m/s)

R: radius of the horizontal curve (m)

G: gravitational acceleration ($m/s^2$)

Since the term tgα in the above expression shows the lateral slope, which is the superelevation, if tgα = q is taken, and the simplified equation becomes:

$$\mathrm{p} = \frac{\mathrm{v}^2}{\mathrm{R}} - \mathrm{g.q} \qquad (3)$$

If the velocity is expressed in km/h (v = V/3.6) and the value of the gravitational acceleration ($g = 9.81\ m/s^2$) is written, the lateral acceleration value becomes:

$$\mathrm{p} = \frac{\mathrm{v}^2}{12{,}96.\mathrm{R}} - 9{,}81.\mathrm{q} \qquad (4)$$

In the above relation, if the lateral acceleration is positive (+), it acts towards the outside of the curve, and if it is negative (-), it acts towards the center of the curve. The maximum value of the lateral acceleration, which does not cause much discomfort during the journey, is accepted as 1.47 $m/s^2$ [1].

Comfort is a characteristic generally used in passenger transportation, and it is a state of physical and mental comfort during the journey [4]. Comfort, which is evaluated from the first to the last point of transportation, is a concept that changes over time and can be perceived in different ways according to gender, age, health status, travel purpose, socio-economic characteristics and mental status of the people.

Comfort for passengers is evaluated by the physiological effects of physical features of transportation, depending on the human organism and mental state. Physical features can be counted as acceleration, vibrations, space arrangement and lighting, air conditioning and noise. The comfort conditions, according to the magnitude of these effects are summarized in Table 1.

The lateral acceleration in the horizontal curve or the lateral acceleration change per unit time is used as the comfort parameter. The comfort parameter is directly linked to human perception, and these parameters may vary for different countries and people. Schofield determined the maximum lateral acceleration value that can be tolerated by the passengers in the vehicle as 2.45 $m/s^2$ for highways and 1.22 $m/s^2$ for railways in his study in 2001 [5]. Again, for railways, Esveld (1989) [6] used 0.80 $m/s^2$, Förstberg (2000) [7] 1.00 $m/s^2$ and Megyeri (1993) [8] used the lateral acceleration limit values of 0.65 $m/s^2$. Apart from these, freedom of movement in the vehicle, various service opportunities, the potentiality of spending the travel time working, attending a conference, reading, and the psychological shortening of the journey by watching movies and television can be added to comfort criteria [9].

The international standard ISO 2631 [10] which is focused on the evaluation of human exposure to whole-body vibration states that weighted root-mean-square acceleration shall be determined at the surface that supports the person in the seated position (i.e. car seat in the case of driving) as follows:

**Table 1.** Change of comfort conditions with physical effects

| Comfort Component | Unit | Comfortable | Bearable | Disturbing | Unbearable |
|---|---|---|---|---|---|
| Vibration (Amplitude) | mm | ≤ 0 | 0-20 | 20-200 | >200 |
| Acceleration | $m/s^2$ | ≤ 0,1 | 0,1-0,2 | 0,2-1,0 | > 1 |
| Oscillation | Degree | ≤ 5 | 5-12 | 12-20 | > 20 |
| Altitude | m | ≤ 1000 | 1000-2000 | 2000-3000 | > 3000 |
| Change of Altitude | m/min | ≤ 60 | 60-100 | 100-300 | > 300 |
| Temperature | °C | ≤ 22 | 22-27 | 27-40 | > 40 |
| Amount of Air | $m^3$/hr | ≥ 30 | 30-19 | 19 - 8 | < 8 |
| Noise | dB(A) | ≤65 | 65-75 | 75-120 | > 120 |

$$a_w = \left[ \frac{1}{T} \int_0^T a_w^2(t)\,dt \right]^{\frac{1}{2}} \tag{5}$$

In Equation 5,

$a_w(t)$: weighted acceleration as a function of time (m/s$^2$)

T: duration of the measurement (s)

The health risk of vibration exposure depends on the duration and for the durations of an average drive (< 2 hours) it is stated that above an acceleration of 1.6 m/s$^2$ health risks are likely.

**Lateral Acceleration Measurement Methods**

Kenda and Kopač (2011) studied with a combination of G-Tech Pro Performance Meter RR w and Performance Analysis System Software (PASS) to analyze the longitudinal acceleration, lateral acceleration, and braking [11]. The acceleration and GPS data collected with the G-Tech device is transferred to the software via a connector to analyze the accelerating and braking patterns of the drive.

A relatively different method involves an optical tire sensor (OTS) and a position-sensitive detector (PSD). The system developed to estimate the lateral state of a vehicle works as follows. A Light Emitting Diode (LED) is attached to the inner side of the tire. The LED lights' position on PSD surface relative to the set positions generates the raw data about the lateral state of the vehicle. The raw data can be processed to extract force, speed, and acceleration values [12,13].

The commonly used instrument to measure lateral acceleration by researchers, local agencies, and highway departments is the ball-bank indicator. The device has a steel ball in a sealed tube, which is free to roll to measure the corresponding lateral acceleration to the tested speed [2]. After it is mounted on a test vehicle, the predetermined horizontal curves are entered with certain speeds with this test tool, and the angle values in the ball-bank device are read. The experiment is repeated several times and these readings are averaged. The average value obtained is compared with the angle value corresponding to the curve project velocity.

There are two different types of this device, mechanical and electronic. The mechanical ball-bank indicator is an assembly formed by a freely moving ball in a curved glass tube filled with a special liquid (Figure 2). As the vehicle moves on the curve, the ball in the device slides outward inside the tube. This ball movement includes the rate of superelevation on the road in degrees of an angle, lateral acceleration, and oscillation of the vehicle body. During the measurement, one person uses the tool, and the other person notes the data obtained from the measurement.

The electronic one, on the other hand, is a device with a digital display on it, which is plugged into the lighter socket in the vehicle and can be connected to the USB port of a laptop with its RS232 output. The LCD shows the angle or superelevation in degrees during the movement around the curve [14]. Electronic ball-bank indicators now replace mechanical ones. Since there is no need for visual reading and taking notes as in the mechanical ones, there is no need for a second person other than the driver under normal conditions however, another person can undertake tasks such as opening, resetting, and controlling the device for a comfortable and safe experiment.

## METHODOLOGY

Methodology followed in the study, is given in Figure 3 as a flow chart.

In the early stages of the study, we reviewed the literature about the definition and calculation of lateral acceleration, perception of this manner and its effect on transportation comfort, and the measurement methods to set our course.

One of the things that this paper suggests is a new method for lateral acceleration measurement. After a detailed search on the Arduino board, GPS and accelerometer models, suitable options were determined. In this regard, a chip named Neo-6Mv2 as the GPS receiver [15], a chip named MMA8451 as the accelerometer [16], and Arduino-UNO as the Arduino board [17,18] were used. A hardware (see Figure 4) combining the accelerometer and GPS that can be mounted on vehicles, was designed using Arduino software and modules to calculate the actual value of the lateral acceleration that occurs during test drives.


**Figure 2.** Mechanical and electronic Ball-Bank indicators.

After separate studies, a program was developed to operate two devices in a coordinated manner. The encodings were adjusted to take the readings simultaneously to make it easier to collect and record acceleration values at certain locations. The integrated model was reached its final form after the validity tests.

As mentioned before, participants were asked to fill out a questionnaire before and during the test drives consisting of two parts: demographical questions and level of comfort perception at each curve on a 5-Point Likert scale. The first part questions were age, gender, height, weight, seat in the car, private car ownership, and transport mode choice. The second part of the survey filled during the drives was about how comfortable they felt at the exact location of each curve's center, shown in Figure 5. Participants ranked their level of comfort from 1 to 5, 1 meaning *"I did not feel any shaking and/or skidding."* and 5 meaning *"I felt a very uncomfortable shaking and/or skidding."*. The Go-Kart track in Yıldız Technical University Davutpaşa Campus was chosen as the test platform. The highway project of the route was drawn to calculate the lateral acceleration limit values and the speeds that give limit values. In the drawing, all curves of the route and the radii of these curves were determined. For each curve, the limit velocity values that form the lateral acceleration limit value of 1.47 $m/s^2$ were calculated. Test drives took place in this stage of the study.

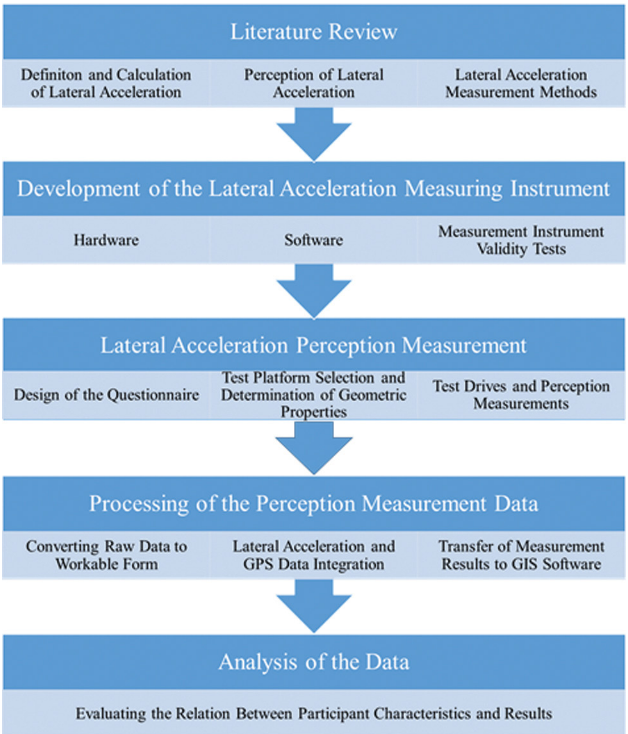


**Figure 3.** Flow Chart for Methodology.

The raw data from GPS and accelerometer, along with the survey data of 20 participants were collected. First, Macro, which is a software that allows us to run the collection of commands to be applied in the MS Excel program in one go, was used to reach the processed data that can be interpreted from the raw state of the data, and these data were made available as input in the following operations. As a result of this process, an Excel file was prepared that contains the locations of the vehicle and the acceleration values at these locations in an orderly and integrated manner. Then, QGIS (Quantum Geographic Information System), a free and open-source Geographic Information System (GIS) software with multi-platform support that provides data viewing, editing, and analysis capabilities, stepped in [19]. The output data file of the previous step was transferred to the QGIS program. The software allowed us to visually examine our location information on the map

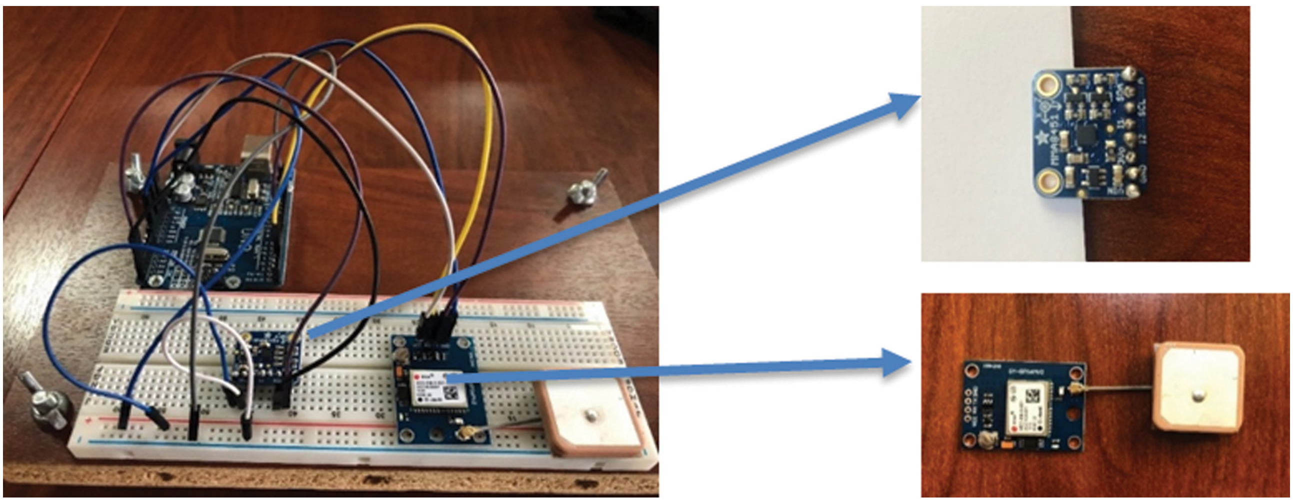

**Figure 4.** Measurement Instrument Hardware.

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**Figure 5.** Test Platform Plan and the ID of Curves.

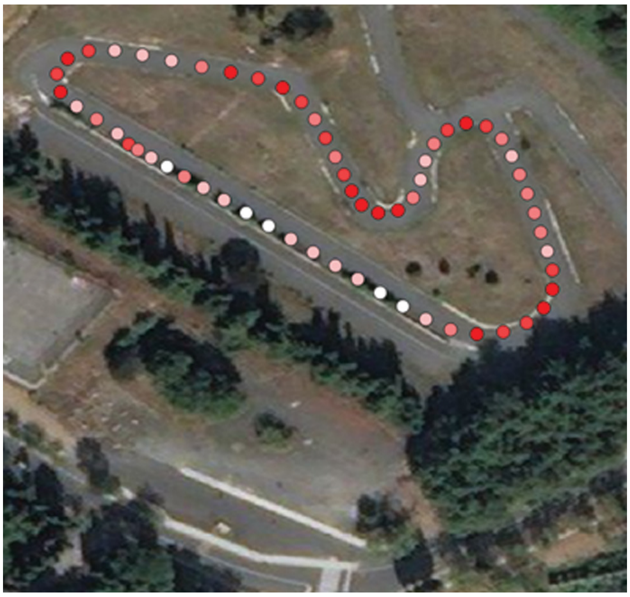

**Figure 6.** QGIS Screenshot of Gradually Visualized Lateral Acceleration Values.

database from Bing. On the other hand, the acceleration values obtained simultaneously with the location data were colored and compared gradually. (see Figure 6)

## DATA

Graphs were prepared to consider which of the parameters influenced the perception of comfort and how much effect they had. In this context, the graphic showing the effect of gender on the perception of comfort is given in Figure 7.

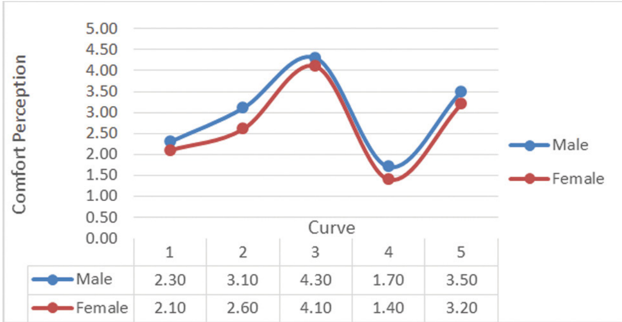


**Figure 7.** The Effect of Gender on Perception of Comfort.

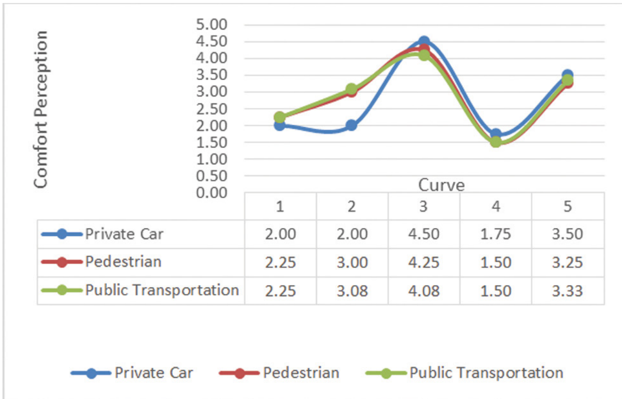


**Figure 8.** The Effect of Preferred Modes of Transport on Perception of Comfort.

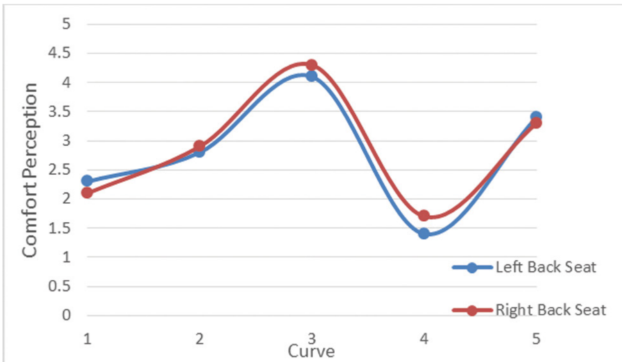


**Figure 9.** The Effect of the Seat in the Vehicle on Perception of Comfort.

On the other hand, the graphic in Figure 8 shows the effect of the transportation mode used by the participants to reach the campus every day on their comfort perceptions.

The relationship between the seat of the participants in the vehicle during their rides and their comfort perception can be seen in Figure 9.

## CONCLUSIONS

The following inferences have been reached about the perception of comfort in university student from the findings of the study that originated from the idea that this globally accepted standard can cause large-scale negative economic consequences.

- It has been observed that men's comfort perceptions are more sensitive than women's, even with a slight difference. Accordingly, men stated that they felt more uncomfortable than women under the same conditions.
- It has been determined that the comfort perceptions of those who reach the campus on foot and those who use public transportation are quite similar. On the other hand, the use of private vehicles decreases young people's comfort expectation in the first two curves while increasing it slightly in the other three curves.
- The seat in the vehicle (left or right seat) has not been observed to significantly affect the participants' comfort perceptions.
- It has been revealed that the lateral acceleration limit value of the highways can be designed with an acceleration value higher than the current 1.47 $m/s^2$ value considering the results obtained from the measurements.

Although we suggest important findings with this study, which has developed a new measurement method about the lateral acceleration limit value -a generally valid standard in highways and has been applied unchanged since 1991- and questions the validity of this value in today's world, the limitation of the study that should not be overlooked is the number of samples. With this in mind, the points that can be considered to improve the research and reach healthier results are as follows.

- The rides can be carried out on a route that has closer geometric features to those in daily life. In this way, more realistic results will be obtained at higher speeds.

The effects of driver behavior on comfort can be investigated by carrying out the test drives with different drivers.

## AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

## DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

## CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

## ETHICS

There are no ethical issues with the publication of this manuscript.

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