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What Makes Passengers Uncomfortable In Vehicles Today? An Exploratory Study of Current Factors that May Influence Acceptance of Future Autonomous Vehicles

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Abstract

Autonomous vehicles have the potential to transform lives by providing transportation to a wider range of users. However, with this new method of transportation, user acceptance and comfort are critical for widespread adoption. This exploratory study aims to investigate what makes passengers uncomfortable in existing vehicles to inform the design of future autonomous vehicles. In order to predict what may impact user acceptance for a diverse rider population for future autonomous vehicles, it is important to understand what makes a broad range of passengers uncomfortable today. In this study, interviews were conducted for a total of 75 participants from three diverse groups, including 20 automotive engineering graduate students who are building an autonomous concept vehicle, 21 non-technical adults, and 34 senior citizens. The results revealed both topics which made different groups of passengers uncomfortable as well as how these varied between the groups. The leading contributors to the highest discomfort for all groups were being a passenger in situations with a distracted driver, being in a vehicle that is following too closely, being near a vehicle that is following too closely, and being in foggy conditions. In addition, the results showed that passenger discomfort can be attributed to a broad range of factors ranging from behaviors of the driver/vehicle that one is traveling with/in, the behaviors of other surrounding vehicles, the environmental conditions and the vehicle's interior, all of which may differ between different groups of passengers. This research provides important findings and insights into factors that may influence users' acceptance and use of future autonomous vehicles.

Introduction

Much of the current research in the autonomous vehicle space has focused on technical aspects of the vehicle, such as how quickly the vehicle changes lanes, how closely the vehicle should follow others, interior ergonomics, passenger safety, etc. This study explored a broad range of factors that make vehicle passengers uncomfortable in today's vehicles with the goal to apply this understanding to future autonomous vehicles.

Passengers' comfort is a topic that has been discussed since the introduction of vehicles into the transportation system [1]. Traditionally, the influential factors of the passengers' riding comfort in a vehicle can be divided into three major categories: dynamic factors, which are related to the acceleration, shock, and vibration during the ride; ambient factors, which are a result of the thermal environment, air quality, noises, etc., in the vehicle; and spatial factors, which are related to the ergonomics of the interiors, including the seating position, interior layout, etc. [2]. Comfort is a factor that has a lasting influence on the users, ranging from the initial vehicle selection to the daily usage. Discomfort in a vehicle can lead to fatigue, which could influence the safety of the vehicle, thus the optimization of comfort creates better conditions for the users [3]. Tremendous efforts in previous research have explored the relationships between these factors that encompass passenger comfort.

For dynamic factors, efforts have focused on finding out the critical features of acceleration or vibration and developing technologies to avoid the uncomfortable dynamics of the vehicle. Oborne's research [4] studied the discomfort from the vehicle's vibration. Both in-laboratory and field studies were carried out and the qualitative and quantitative relationship between vehicular vibration and passenger comfort were discussed. An elevation in discomfort is expected as the intensity increases until the acceleration of vibration reaches 1.4 m/s^2. After that, the discomfort of the passenger is more likely to result from motion sickness instead of the vibration itself. The work by Wu [5] constructed a car control model dedicated to reducing the passengers' discomfort caused by braking. This model focused on longitudinal acceleration instead of vertical acceleration which has been discussed more in a traditional comfort model [6] and is able to determine the brake deceleration that is more comfortable for the passengers in the vehicle.

Efforts examining ambient factors have focused on the development of constructing mathematical models on factors such as thermal comfort and noise. Nor [7] calculated models to describe the relationship between several vehicular acoustic features and the subjective comfort level of the passenger. In their experiments, an acoustical manikin was used to record the objective acoustical features when the vehicle was driving on different types of roads and the subjective ratings of comfort were taken with participants sitting in the vehicle using a 5-point Likert scale. The relationships between the objective and subjective measurements were extracted. The loudness was found to have a high correlation with the subjective acoustical comfort in all road types and the sharpness was found to have a medium to high correlation in different types of roads. Mezrhab [8] built a mathematical model of the heat transfer inside a vehicle. This model can help the simulation of the thermal condition inside a vehicle to find a solution to decrease the power consumption of the air conditioning system while maintaining a proper temperature for the passengers.

Research on spatial factors of comfort have primarily focused on the interior design in the vehicle. Kyung and colleagues in a two-part series of studies published in 2008 [9,10] examined different approaches to measure the seating comfort of drivers. Both subjective and objective approaches were studied. The subjective measurement method utilized two 10-point Likert scales for comfort and discomfort ratings respectively and the participants in the experiment used these two scales to rate their feelings from six different parts of the body including bilateral thighs and buttocks, as well as the lower and upper back after sitting on a seat for a given period. The objective measurement used a pressure mat that measures the pressure of the interaction between the seat and the body, then the results from the mat were compared with the data gathered from the subjective approach. For these subjective measurements, the discomfort scale was to effectively measure the basic qualities of a seat, which ensures no violation of basic seat requirements or design rules; the comfort scale was useful in measuring the more subtle qualities of a seat, which promotes advanced seat requirements of comfort. The pressure mat measurement was found to be helpful in assessing short-term comfort/discomfort, but not for long-term assessments. Park [11] developed an index called the Q index to evaluate the ability of a vehicle's interior design to accommodate drivers of different size. The Q index of an interior was calculated by examining the portion of the preferred adjustment configurations, i.e., the steering wheel and the seat position configurations, by a group of drivers that can be accommodated by this design. This index was a supplement to the evaluation tools of the vehicle's interior design.

The automotive industry is working towards autonomous or self-driving vehicles. Though there are varying levels of automation outlined by the Society for Automotive Engineers (SAE), the highest level of automation (SAE level 5) does not require the user to drive [12]. With the introduction of autonomous vehicles (SAE level 5), a series of factors that were not included in the riding comfort factors discussed in the previous work [2] need to be considered. This is because of the lack of control from a driver and the additional factors that include but are not limited to human-like and disturbance-free control, apparent safety, and motion sickness [13]. Some factors that have been discussed under human-robotic interaction (HRI) are also being included into the research topics of passengers' comfort in autonomous vehicles. The work by Morales [14] developed a visibility model to assist with more comfortable navigation of an autonomous vehicle. The concept of visibility was initially researched in robotic mapping problems [15, 16, 17] and it is under discussion in autonomous vehicles as a comfort related topic. This work inspired our team to dig deeper into the HRI field for helpful clues to autonomous vehicle comfort studies.

Much of the current research surrounding autonomous vehicles and passenger comfort relates to driving style. To further explore different driving styles, researchers have focused on specific maneuvers that a passenger would experience while riding in an autonomous vehicle. Many of these studies utilize simulators to compare the autonomous systems' behavior to human driven vehicles' behavior. For passing or overtaking maneuvers, passengers preferred longer headway distances when initiating a maneuver [18]. Passengers also preferred early action and reduced jerkiness when performing a lane change as well as during acceleration and deceleration [19]. Some studies have explored differences between different user groups. Interestingly, younger drivers preferred the autonomous vehicle's driving style to resemble their own style, while older drivers preferred an unfamiliar driving style [20].

It is uncertain how fully autonomous vehicles will look in the future. Since fully autonomous vehicles will not depend on a dedicated driver, this allows for greater flexibility and scope for the vehicle interior design compared to constraints in current vehicles. Allowing for flexible seat positioning, and orientations, has been shown to be preferred for long distance travel [21]. However, these more flexible seating configurations and orientations open new potential user experiences while raising safety concerns [22]. Therefore, a broader analysis of all the factors to be considered in future vehicle design is needed.

While existing research on vehicle comfort has mainly focused on dynamic factors, ambient factors, and spatial factors, there are still many other factors and even some new factors, which may potentially be introduced by future vehicle autonomy efforts such as the vehicle's behavior and interactions with the surroundings. The previous research has been dedicated to finding approaches to identify the relationship of or improvement of the influence between different factors and the passenger's comfort. The investigation of comfort factors considered by a wide range of users with different demographic backgrounds, such as age and experience, are critical for widespread adoption of autonomous vehicles.

Our lab's research on this topic began with an investigation of four diverse users' needs and wants for a fully autonomous vehicle [23]. In-depth interviews and day-in-the-life experiences provided the team with an understanding of the needs and constraints of very different types of users including: a millennial with a visual impairment, a professional in a major metropolitan area who does not want to drive yet needs to transport influential clients to meetings throughout the city, a full-time working mom with 3 kids under the age of 12, and a designer who is a quadriplegic who lives as independently as possible while using a large motorized wheelchair. The findings concluded that each of these users had very different requirements or needs in order to utilize the vehicle, but interestingly, all four users wanted the vehicle to be safe and secure, reliable, and a good value or affordable. Future autonomous vehicles will have vastly different metrics for user satisfaction than what exists today.

Next, our lab interviewed certified driving rehabilitation specialists (CDRSs) who are typically occupational therapists that evaluate and train clients who have medical conditions that impact their ability to drive due to visual, cognitive, and/or motor issues. Due to the CDRSs unique perspective from spending a large amount of time in the passenger's seat while working with their clients, they were the pilot participants for this research [24]. The interviews with the CDRSs aimed to understand what factors made these clinicians uncomfortable when riding with their clients as well as during their personal time. The majority of the factors that made CDRSs uncomfortable both when riding with clients and during their personal time stemmed from the environment (fog, unfamiliar, dense traffic), actions of the driver (being distracted, following too closely, changing lanes), and the actions of drivers in other vehicles (following too closely, being distracted). When riding with clients, there was an increase in the number of CDRSs who reported being uncomfortable with the driver-related factors than during their personal time [24]. These initial interviews were helpful to be able to develop the more structured interview used in the current study. Thus, the current paper uses a multifaceted definition of comfort to encompass physical, psychological, and environmental elements to explore passenger comfort between different user groups.

To this end, the research presented in this paper builds upon the interviews with the CDRSs [24] and aims to give a more comprehensive investigation on passenger discomfort in today's vehicles in order to help better understand potential factors that may influence the use of future autonomous vehicles. While the present study builds upon the previous interviews with the CDRSs, this research is still exploratory in nature and focuses on a broad range of factors in addition to traditional automotive comfort factors. Particularly, actions of the vehicle the passenger is traveling in, interactions with surroundings and human-vehicle interactions are investigated. To expand upon previous research and broaden the groups of users explored, this study includes three groups of participants with different backgrounds: automotive engineering graduate students who are building an autonomous concept vehicle, non-technical adults and senior citizens. The purpose of having three diverse groups of participants was to explore the comfort factors of different generations. These groups were selected to represent the technology adoption lifecycle, where the automotive engineering graduate students likely represent the early adopters that have a greater understanding of the technology, adults being in the middle, and seniors representing individuals that may lag in adopting new technology. The seniors were also critical to understanding how comfort changes with age. In the following sections of this paper, the methodology, including the survey and participant demographics, is described. The summary of the responses for each of the survey questions are presented in the results. The discussion focuses on comparing and summarizing the most relevant factors that cause discomfort, differences observed between the groups, the limitations of the study and suggestions for future studies, followed by the overall conclusions.

Materials and Methods

Participants

Volunteers were 18 years of age or older. Three diverse user groups were selected for this study: 1) second year automotive engineering graduate students who were building an autonomous concept vehicle, 2) non-technical adults (who were not engineers or computer scientists) and 3) seniors from a local community organization that provide services for adults over 55 years of age. The automotive engineering students included 21 participants; one participant's data was dropped due to a technological recording issue. Of the 20 participants, ages ranged from 23 to 29 years with an average of 25.2 years, with 17 males and three females. There were 21 adult participants with an average age of 34.4 years, ranging from 20 to 52 years of age. Adults consisted of four males and 17 females. The 34 seniors ranged from 62 to 87 years, with an average age of 72.9 years. There were 11 senior males and 23 females. The reason the seniors had a larger sample was simply a pragmatic issue. There were two data collection periods at the community center and all individuals who volunteered to participate during those periods participated in the study. The goal was to have a minimum of 20 volunteers per group.

Procedure

Automotive engineering graduate students, adult and senior participants were recruited from the university, community and senior center located in the Upstate of South Carolina respectively, using flyers and in-person recruiting. Due to the exploratory nature of the study, structured interviews were utilized to allow participants the freedom to be able to make additional comments, providing richer information. The interviews were conducted in-person by one of multiple members of the research team who asked the participant questions and recorded their responses. The interviews for the students took place at the university, the interviews with the adults took place throughout the community, and the interviews with the seniors took place at the senior center. The study was approved by the Ethics Committee (Institutional Review Board) at Clemson University. Participants were compensated for their time with a $15 Visa gift card. Participants were asked to respond to the questions from the perspective of being a passenger in today's passenger vehicles because fully autonomous vehicles are not available to the public, thus it would be difficult for participants to imagine using autonomous vehicles. For the interview questions please see Appendix A: Interview questions, topics and response types from the interview adapted from our lab's previous wok [24].

Data Analysis

The interviews consisted of several questions where participants simply responded "yes" or "no". The results for the "yes" and "no" questions are presented as percentages. Since each participant was asked to respond to each of the situations or environments in a given topical area, the percentage of participants that responded "yes" for that situation or environment is presented. Therefore, the sum of the situations or environments in the table may sum to a value greater than 100%. This method was used to aid comparisons across groups due to different sample sizes.

After responding to the list of situations or environments for a given topic, all participants were asked if there were any other comments they wanted to add in an open-ended format. In order to compare open-ended responses between groups, each groups' responses were sorted by grouping similar responses together to form categories. The total number of responses in each category were totaled and then compared across the groups. The results are reported as a percentage of the total number of responses for each group, which sums to 100% in the tables. If participants could give multiple responses, that is noted on each table. Responses 40% or greater are in italics, responses 60% or greater are in italics plus bold and responses 80% or greater are in italics, bold plus underlined. The items categorized as other were all less than the smallest percentage for any individual user group; these items were all unique and did not overlap with any of the other groups. The sample size is included in each table in cases where the full sample did not answer a given question. The open-ended items as well as the items classified as other are in italics in the tables. Two team members sorted and categorized all data independently prior to checking for agreement. Any inconsistencies between the two team members were discussed and reconciled for each response, which is similar to the rating process in the automotive industry for comprehension testing of in-vehicle symbols, SAE J2830 [25].

For the questions with the "yes" or "no" response type, Chi-square Tests of Independence were conducted to determine if there were differences between the three participant groups. When differences were discovered between the three groups, posthoc Chi-square tests were conducted using a Bonferroni adjustment method. Because there were six comparisons being made, posthoc Chi-square tests were evaluated at a significance level of 0.008.

Results

Driver Versus Passenger Preference

All participants were asked if they preferred being the driver or the passenger, as well as the reason for their response. The majority of participants preferred being the driver including ***70%*** of the automotive engineering students, ***76.2%*** of the adults and <u>***82.4%***</u> of the seniors. When asked why they prefer to be the driver, wanting to have control was the most frequent response for the adults (*57.9%*) and the seniors (*40.0%*). The engineering students had a very different primary reason, specifically they enjoyed driving (***66.7%***).

Some participants from each group preferred to be the passenger, including 6 engineering students (30%), 5 adults (23.8%), and 6 seniors (17.6%). When asked why they prefer to be the passenger, the most frequent response was participants were not confident in their driving skills for the engineering students (33.3%) and the adults (28.6%). Both the adults and seniors identified having the ability to do another task such as look outside, 28.6% and 22.2% respectively, as a frequent reason for preferring being the passenger. For the seniors, relaxing / break from driving (33.3%) was the most common response.

Discomfort as a Passenger

All participants were asked if they had ever felt uncomfortable as a passenger in a vehicle. Across the groups, the majority of participants had felt uncomfortable as the passenger including *50.0%* of the engineering students, ***61.9%*** of adults, and ***73.5%*** of seniors.

As a follow-up, the participants were asked to describe what made them uncomfortable using an open-ended question. Table 1 highlights the most common responses from each group; interestingly they do not overlap much between the groups. The engineering students reported feeling uncomfortable due to a reckless / aggressive driver (13.3%), seat comfort / adjustment (13.3%), being in the backseat (13.3%), and a crowded vehicle (13.3%). The adults' most common responses were due to seat comfort / adjustment (19%) and heating, ventilation, and air conditioning (HVAC) controls (14.3%). For the seniors, the most frequent reasons contributing to their discomfort as a passenger were fast driving (17.9%), following too closely / tailgating and slamming on brakes (10.3%), being anxious / nervous about others driving (10.3%), seat discomfort / adjustment (10.3%), and being in the backseat (10.3%).

Discomfort Due to Sounds

The interview asked all participants if they were ever uncomfortable due to sounds. More than half of the adults (*52.4%*) reported feeling uncomfortable due to certain sounds, where the engineering students (*45.0%*) and seniors (*44.1%*) had lower response rates.

For the participants that reported being uncomfortable due to sounds were asked whether the sounds were "inside the

TABLE 1 Reasons for feeling uncomfortable as a passenger

Reasons for discomfort as a passenger	10 Engin. Students (N=15)[1]	13 Adults (N=21)[1]	25 Seniors (N=39)[1]
Seat discomfort / adjustment	13.3%	19.0%	10.3%
Reckless / aggressive driving	13.3%	4.8%	0.0%
Being in the backseat	13.3%	0.0%	10.3%
Crowded vehicle	13.3%	0.0%	2.6%
HVAC controls	6.7%	14.3%	0.0%
Weather / changing conditions	6.7%	4.8%	0.0%
Driver is distracted / not paying attention	6.7%	0.0%	5.1%
Love / like driving	6.7%	0.0%	2.6%
Driver lacks skills / has poor driving skills	6.7%	0.0%	0.0%
Fast driving	0.0%	9.5%	17.9%
Not a preferred driver	0.0%	9.5%	7.7%
Traffic	0.0%	9.5%	0.0%
Anxious / nervous about others driving	0.0%	4.8%	10.3%
Spouse is driving	0.0%	4.8%	5.1%
Older driver	0.0%	4.8%	2.6%
Driver is following too closely / tailgating and slamming on brakes	0.0%	0.0%	10.3%
Car is small	0.0%	0.0%	5.1%
Other	13.3%	14.3%	10.3%

[1] Participants could give multiple responses. *N* indicates the number of responses per group.

Note: The open-ended items as well as the items classified as other are in italics in the tables.

vehicle", "outside the vehicle", or "both". For the engineering students (*44.4%*) and seniors (*46.7%*), the most common response was outside the vehicle, while the adults' (*45.5%*) most common response was both inside and outside the vehicle.

Participants were further asked to describe sounds that made them uncomfortable. The engineering students and adults reported rattling noises and loud music inside the vehicle made them feel uncomfortable while the seniors reported loud music (*42.9%*) and other passengers' conversations / noise level (28.6%). For the sounds outside of the vehicle that caused discomfort, the engineering students identified wind noise (27.1%), road / tire noise (18.2%), and abnormal noises (anything that is not a normal noise; 18.2%) as the most common responses. The two outside sounds that the adults reported most frequently included traffic / noise from other vehicles (*40%*) and road / tire noise (20%). Road / tire noise (23.1%), abnormal noises (23.1%) and loud music (23.1%) were the sounds outside the vehicle that seniors reported caused the most discomfort.

Discomfort Not Being Able to See Out

All three groups of participants were uncomfortable because they could not see out while riding in a vehicle or public transportation. ***Seventy-five percent*** of the engineering students, ***76.2%*** of the adults and ***61.8%*** of the seniors reported being uncomfortable when unable to see out.

Motion / Car Sickness

All participants were asked if they experienced motion or car sickness when riding as a passenger. A smaller number of the seniors (26.5%) reported experiencing motion or car sickness in comparison to the engineering students (*55%*) and the adults (**66.7%**). The Chi-square test indicated that there was a significant difference between these groups ($\chi^2(2) = 9.49$, $p < .05$). The posthoc Chi-square tests determined there was a significant difference between the number of adults that experienced motion or car sickness and the seniors ($\chi^2(1) = 8.62$, $p < .008$).

Discomfort Due to the Driver

All participants were asked if they ever felt stress or discomfort as a result of the driver. All interview participants responded to a list of situations and vehicle maneuvers to determine if any of the topics made them feel stressed or uncomfortable (see Table 2). For the engineering students, driver distraction (**95.0%**), following too closely (***75%***) and passing a tractor-trailer that has two trailers (***75.0%***) were the most frequent responses. Similarly, the adults reported the most uncomfortable maneuvers were when the driver is following too closely (**100%**), distracted (**95.2%**), decelerates or slows down quickly (**85.7%**), passing a tractor-trailer (**85.7%**), and passing a

TABLE 2 Percentage of participants that responded "yes", indicating that they felt uncomfortable/stressed as a passenger in a vehicle in a given situation or when the driver performs various maneuvers

Situations or various vehicle maneuvers performed by the driver	20 Engin. Students	21 Adults	34 Seniors
When the driver is distracted	***95.0%***	***95.2%***	***100.0%***
Is following too closely	***75.0%***	***100.0%***	***88.2%***
Is passing a tractor-trailer that has two trailers (one 18-wheeler pulling two trailers)	***75.0%***	***85.7%***	***73.5%***
Decelerates or slows down quickly	***65.0%***	***85.7%***	***64.7%***
Is passing a tractor-trailer (18-wheeler)	***65.0%***	***85.7%***	***64.7%***
Is merging	*40.0%*	*57.1%*	*55.9%*
Accelerates quickly[1]	25.0%	*57.1%*	***67.6%***
Is passing a vehicle	20.0%	*42.9%*	*50.0%*
Has a child under the age of 5 in it	20.0%	33.3%	29.4%
Is changing lanes[2]	15.0%	33.3%	*52.9%*
Has a pet in it	15.0%	23.8%	38.2%

[1] The Chi-square test on when the driver accelerates quickly indicated that there was a significant difference between these groups ($\chi^2(2) = 9.37$, $p < .05$). The post hoc Chi-square tests determined that the number of seniors that reported discomfort when the driver accelerates quickly was significantly higher than the engineering students ($\chi^2(1) = 9.17$, $p < .008$).

[2] The Chi-square test on when the driver is changing lanes indicated that there was a significant difference between these groups ($\chi^2(2) = 9.49$, $p < .05$). The post hoc Chi-square tests determined that the number of seniors that reported discomfort when the driver is changing lanes was significantly higher than the engineering students ($\chi^2(1) = 7.63$, $p < .008$).

tractor-trailer that has two trailers (**85.7%**). The vehicle maneuvers that made the seniors feel uncomfortable as passengers were when the driver is distracted (**100%**), following too closely (**88.2%**) and passing a tractor-trailer with two trailers (***73.5%***). The majority of the maneuvers had 50% or more participants respond "yes" to feeling uncomfortable when the driver performed them, except for having a pet in the vehicle and having a child under the age of 5 in the vehicle.

Participants were given the opportunity to describe other maneuvers or situations where they felt stressed or uncomfortable because of the driver. For the engineering students, being a passenger on curvy mountain roads (*50.0%*) and an aggressive driver (25%) were the most frequent. The adults reported that sudden movements or weaving (*50.0%*) made them feel uncomfortable as a passenger. In the group of seniors, one participant reported that the normal stopping of the vehicle made them feel uncomfortable.

What Makes Someone a Poor Driver

All participants were asked to describe what made them uncomfortable or nervous when riding with someone they consider a poor driver. This was an open-ended question; there was tremendous variability in the responses (see Table 3). The engineering students' most frequent reasons were slamming on the brakes / late-braking (14.3%), being distracted / not paying attention (11.9%), and reckless driving (11.9%). The adults and seniors both reported the same top three reasons, specifically a driver that is distracted / not paying attention, speeding, and tailgating.

TABLE 3 Reasons for discomfort when riding with a poor driver

Reasons someone is a poor driver	20 Engin. Students (*N*=42)[1]	21 Adults (*N*=52)[1]	34 Seniors (*N*=60)[1]
Slamming on brakes / late-braking	14.3%	7.7%	1.7%
Distracted / not paying attention	11.9%	15.4%	18.3%
Reckless driving	11.9%	0.0%	1.7%
Sudden changes in speed / jerkiness	9.5%	1.9%	0.0%
Does not follow road rules	9.5%	1.9%	0.0%
Speeding	7.1%	15.4%	18.3%
Changing lanes too fast / frequently	4.8%	7.7%	6.7%
Not changing gears smoothly	4.8%	0.0%	0.0%
Poor decision making / judgement	2.4%	3.8%	6.7%
Not using turn signals	2.4%	3.8%	5.0%
Not wearing their seatbelt	2.4%	3.8%	0.0%
Everything	2.4%	3.8%	0.0%
High crash potential / fear of being in crash	2.4%	1.9%	1.7%
Merging	2.4%	1.9%	0.0%
Tailgating	0.0%	15.4%	15.0%
Driving too slowly	0.0%	1.9%	6.7%
Poor lane position / management	0.0%	1.9%	3.3%
Cutting others off	0.0%	1.9%	3.3%
Not attentive to the environment	0.0%	1.9%	0.0%
Unpredictability of the driver	0.0%	0.0%	1.7%
Other	11.9%	7.7%	10.0%

[1] Participants could give multiple responses. *N* indicates the number of responses per group.

Note: The open-ended items as well as the items classified as other are in italics in the tables.

Discomfort Due to Other Vehicles on the Road

All participants were next asked if they felt stressed / uncomfortable as a passenger when the driver performed various vehicle maneuvers (see Table 4). When another driver is distracted (**90.0%**), following too closely (**80.0%**) and decelerates or slows down quickly (***70.0%***) were the primary reasons of distress for the engineering students. For the adults, the most common reasons were when other drivers are following too closely (**95.2%**), are distracted (**95.2%**) and decelerate or slow down quickly (**85.7%**). Similarly, for the seniors, the most common actions other drivers make that cause discomfort include when the driver is distracted (**97.1%**), following too closely (**91.2%**) and passing a tractor-trailer with two trailers (***70.6%***).

Participants were given the opportunity to add other maneuvers or situations performed by other drivers that caused them stress or discomfort. There were very few responses from both the engineering students (*N*=3) and seniors (*N*=1), where both groups' only overlapping response was not using turn indicators. The adults only had one response, which was ignoring the rules of the road.

Discomfort Due to the Environment

Next, all participants were asked questions which focused on environments outside of the vehicle (see Table 5). The engineering students reported fog (**80.0%**), ice (**80.0%**), heavy rain

TABLE 4 Percentage of participants that responded "yes", indicating that they felt uncomfortable / stressed as a passenger when other vehicles perform various maneuvers

Various vehicle maneuvers performed by other drivers	20 Engin. Students	21 Adults	34 Seniors
When the driver is distracted	***90.0%***	***95.2%***	***97.1%***
Is following too closely	***80.0%***	***95.2%***	***91.2%***
Decelerates or slows down quickly	***70.0%***	***85.7%***	***67.6%***
Is merging	*55.0%*	***61.9%***	***67.6%***
Is changing lanes	*45.0%*	***71.4%***	***67.6%***
Is passing a tractor-trailer that has two trailers (one 18-wheeler pulling two trailers)	35.0%	***71.4%***	***70.6%***
Accelerates quickly	30.0%	***61.9%***	***61.8%***
Is passing a vehicle	30.0%	***61.9%***	*50.0%*
Is passing a tractor-trailer (18-wheeler)[1]	20.0%	***71.4%***	***64.7%***
Has a pet in it	10.0%	14.3%	29.4%
Has a child under the age of 5 in it	5.0%	19.0%	23.5%

[1] The Chi-square test on when other drivers are passing a tractor-trailer indicated that there was a significant difference between these groups ($\chi^2(2) = 13.46$, $p < .05$). The post hoc Chi-square tests determined that the number of engineering students that reported discomfort when other drivers are passing a tractor-trailer was significantly lower that the adults ($\chi^2(1) = 8.62$, $p < .008$) and the seniors ($\chi^2(1) = 7.69$, $p < .008$).

TABLE 5 Percentage of participants that responded "yes", indicating that they felt uncomfortable / stressed as a passenger in different environments

Various environments that caused stress / discomfort	20 Engin. Students	21 Adults	34 Seniors
In fog	80.0%	90.5%	94.1%
In heavy rain	80.0%	90.5%	91.2%
When there is ice	80.0%	85.7%	97.1%
When it is raining at night	80.0%	81.0%	91.2%
In the snow	70.0%	81.0%	76.5%
In unfamiliar environments	70.0%	71.4%	52.9%
On curvy mountain roads	65.0%	85.7%	73.5%
At night	55.0%	66.7%	67.6%
On bumpy roads or challenging terrain	45.0%	61.9%	64.7%
On curvy roads[1]	40.0%	81.0%	52.9%
In the rain	40.0%	61.9%	50.0%
In dense traffic[2]	20.0%	76.2%	79.4%
On empty roads	20.0%	14.3%	11.8%

[1] The Chi-square test on curvy roads indicated that there was a significant difference between these groups ($\chi^2(2) = 7.51, p < .05$). The post hoc Chi-square tests determined that the number of adults that reported discomfort on curvy roads was significantly higher than the engineering students ($\chi^2(1) = 7.22, p < .008$).

[2] The Chi-square test on dense traffic indicated that there was a significant difference between these groups ($\chi^2(2) = 21.28, p < .05$). The post hoc Chi-square tests determined that the number of engineering students that reported discomfort in dense traffic was significantly lower that the adults ($\chi^2(1) = 12.95, p < .008$) and the seniors ($\chi^2(1) = 18.18, p < .008$).

TABLE 6 Percentage of participants that responded "yes", indicating that they felt uncomfortable / stressed as a passenger in different vehicle conditions

Various vehicle conditions that caused stress or discomfort	20 Engin. Students	21 Adults	34 Seniors
Needs to be cleaned due to body odor	90.0%	95.2%	76.5%
Needs to be cleaned due to pet odors	90.0%	85.7%	76.5%
Needs to be cleaned due to mystery stains	90.0%	85.7%	70.6%
Smells like cigarettes	88.9% [1]	90.5%	85.3%
Has a leaking window	83.3% [1]	81.0%	82.4%
Needs to be cleaned due to food odor	80.0%	81.0%	67.6%
Needs to be vacuumed due to candy wrappers and food crumbs on the seats	80.0%	61.9%	50.0%
Needs to be cleaned due to dust or dirt on the dashboard[2]	75.0%	33.3%	41.2%
Has maintenance light(s) on	70.0%	81.0%	82.4%
Needs to be vacuumed due to long hair on the seats and floor	70.0%	61.9%	55.9%
Needs to be cleaned due to pet fur	70.0%	57.1%	55.9%
Has warning light(s) on	65.0%	76.2%	82.4%
Needs to be cleaned due to perfume odor	45.0%	42.9%	55.9%
Is very small like a hatchback	40.0%	61.9%	38.2%
Needs to be vacuumed due to grass or dirt on the floor from shoes	40.0%	23.8%	20.6%
Is a 15-passenger van	20.0%	23.8%	23.5%
Is a sedan	10.0%	14.3%	8.8%
Is a large SUV	10.0%	9.5%	11.8%

[1] N=18 for the engineering students.

[2] The Chi-square test on the vehicle needs to be cleaned due to dust or dirt on the dashboard indicated that there was a significant difference between these groups ($\chi^2(2) = 8.29, p < .05$). The post hoc Chi-square tests determined that the number of engineering students that reported discomfort due to dust or dirt on the dashboard was significantly higher than the adults ($\chi^2(1) = 7.15, p < .008$).

(**80.0%**) and rain at night (**80.0%**) as the environments where they felt uncomfortable as a passenger. For the adults, the environments that cause the most discomfort were fog (**90.5%**), heavy rain (**90.5%**), ice (**85.7%**) and curvy mountain roads (**85.7%**). Lastly, the environments with the highest percentages for the seniors were ice (**97.1%**), fog (**94.1%**), heavy rain (**91.2%**), and rain at night (**91.2%**).

Like previous interview questions, participants were asked to identify any other environments where they felt stressed or discomfort. Hail was the only overlapping item reported by the engineering students (N=3, 33.3%) and adults (N=1, **100.0%**). The seniors (N=3) reported oncoming glare (***66.7%***) and high winds (33.3%).

Discomfort Due to the Vehicle

All participants were asked if they ever experienced stress or felt uncomfortable due to the vehicle that they were riding in as a passenger. The engineering students reported being more uncomfortable due to pet odors (**90.0%**), body odor (**90.0%**) and cigarette odor (**88.9%**) in addition to mysterious stains (**90.0%**). The adults had similar responses with their top two responses being body odor (**95.2%**) and cigarette odor (**90.5%**). For the seniors, the smell of cigarettes (**85.3%**) caused discomfort, but unlike the other groups, warning lights (**82.4%**), maintenance lights (**82.4%**) and a leaking window (**82.4%**) were the most frequent responses (see Table 6).

Discomfort Due to the Temperature or Airflow

All participants responded to a list of conditions related to temperature and airflow, see Table 7. The three most frequent responses for the engineering students were when there is no airflow (**90.0%**), the temperature is too cold (**80.0%**) and the temperature is too warm (***70.0%***). Similarly, the adults' most common responses were when the temperature is too cold (**85.7%**), when the temperature is too warm (**85.7%**) and when the cooled seats are on (***76.2%***). For the seniors, loud music (**88.2%**), lack of airflow (**85.3%**) and the temperature is either too cold (***76.5%***) or too warm (***73.5%***) were situations that cause stress or discomfort.

Vehicle Most Comfortable In

All participants were asked what type of vehicle they were most comfortable riding in, see Table 8. The engineering students were most comfortable in a medium to large sedan (*57.1%*) and a compact or small SUV / crossover (23.8%). Medium to large SUVs (*50.0%*) were the most common vehicle reported by the adults. The seniors were most comfortable in either a medium to large sedan (*40.0%*) or a medium to large SUV (25.7%).

TABLE 7 Percentage of participants that responded "yes", indicating that they felt uncomfortable / stressed as a passenger due to conditions related to temperature or airflow

Various temperature or airflow conditions that caused stress or discomfort	20 Engin. Students	21 Adults	34 Seniors
When there is no airflow	***90.0%***	*66.7%*	***85.3%***
The temperature is too cold	***80.0%***	***85.7%***	***76.5%***
The temperature is too warm	***70.0%***	***85.7%***	***73.5%***
When the music is too loud[1]	*44.4%*	4.8%	***88.2%***
The windows are open	25.0%	4.8%	*44.1%*
The cooled seats are on	15.0%	*76.2%*	14.7%
The heated seats are on	15.0%	9.5%	20.6%

[1] The Chi-square test on when the music is too loud indicated that there was a significant difference between these groups ($\chi^2(2) = 16.49$, $p < .05$). The post hoc Chi-square tests determined that the number of seniors that reported discomfort when the music is too loud was significantly higher than the engineering students ($\chi^2(1) = 11.83$, $p < .008$).

TABLE 8 Type of vehicle that participants felt most comfortable riding in

Vehicle types most comfortable riding in	20 Engin. Students	21 Adults	34 Seniors
Medium to large sedan	*57.1%*	9.1%	*40.0%*
Compact or small SUV / crossover	23.8%	13.6%	5.7%
Medium to large SUV	4.8%	*50.0%*	25.7%
Pick-up truck	4.8%	9.1%	17.1%
Minivan or large SUV with 3 rows	4.8%	9.1%	2.9%
Small car	4.8%	4.5%	5.7%
Full size van	0%	4.5%	0%
No preference	0%	0%	2.9%
Sports car	0%	0%	0%

TABLE 9 Percentage of participants that responded "yes", indicating that they felt uncomfortable / stressed as a passenger in different positions

Positions in the vehicle that caused stress or discomfort	20 Engin. Students	21 Adults	34 Seniors
The third row in an SUV or minivan[1]	***90.0%***	*71.4%*	*44.1%*
The middle position between two seats	***85.0%***	*66.7%*	*55.9%*
The backseat in a two-door coupe	***80.0%***	***85.7%***	*67.6%*
A seat without a headrest	*77.8%*[2]	*57.1%*	*50.0%*
A seat that is not facing forward	*60.0%*	*76.2%*	*58.8%*
The bed of truck	*50.0%*	***81.0%***	***73.5%***
The back seat	*50.0%*	*76.2%*	*50.0%*
The front seat	10.0%	0.0%	14.7%

[1] The Chi-square test on sitting in the third row in an SUV or minivan indicated that there was a significant difference between these groups ($\chi^2(2) = 13.79$, $p < .05$). The post hoc Chi-square tests determined that the number of engineering students that reported discomfort sitting in the third row in an SUV or minivan was significantly higher than the seniors ($\chi^2(1) = 12.43$, $p < .008$).

[2] N=18 for the engineering students.

Positions in a Vehicle that Cause Discomfort

All participants were asked if there were specific positions in the vehicle that are more uncomfortable compared to others. The engineering students said the third row in an SUV or minivan (**90.0%**), the middle position between two seats (**85.0%**) and the backseat in a two-door coupe (**80.0%**) were the most uncomfortable. The adults reported the backseat in a two-door coupe (**85.7%**) and the bed of a truck (**81.0%**) as the most uncomfortable position. For the seniors, the bed of a truck (***73.5%***) and the backseat in a two-door coupe (***67.6%***) were the most uncomfortable positions within a vehicle (see Table 9).

Discussion

This study aimed to investigate passenger discomfort in vehicles from diverse groups of users. The groups included automotive engineering graduate students in their second year of graduate school, who were building a fully functioning autonomous vehicle, non-technical adults, and senior citizens. Understanding passenger comfort in today's vehicles will help to inform the influential factors that may impact the use of future autonomous vehicles.

The structured interview was separated into multiple topical sections ranging from focusing on potential areas of passenger discomfort due to the driver of the vehicle one is riding in, other vehicles on the road, the environmental conditions, the vehicle's interior, the vehicle's temperature or airflow and seating position in the vehicle. Though there were items that caused more discomfort than others in each section, the discussion will focus on the trends across the groups. Table 10 summarizes and rank orders passenger's attitudes across all items that led to higher ratings of discomfort. In Table 10, the greater the number of check marks and the darker the gray, the greater the passenger discomfort. The table shows there are some items that causes discomfort for all of the groups, such as being the passenger in a vehicle where the driver is distracted.

Driver distraction and following too closely topics are four of the five primary reasons that caused the participants to be uncomfortable in vehicles as passengers across all three user groups. In 2020, distracted driving was associated with eight percent of fatal crashes in the US and 14 percent of crashes with injuries [26]. Driver distraction [27] and following too closely [28], also known as tailgating, were two frequently cited contributing factors in car crashes. It is interesting that overall, the situations causing the most discomfort are also connected to crashes that are primarily caused by human error [27]. Participants consider both driver distraction (97%) and tailgating (88%) to cause more discomfort when the behaviors occurred within the vehicle they are traveling in compared to other vehicles.

Four weather conditions, including fog (88%), ice (88%), heavy rain (87%), and raining at night (84%) were included in the top ten reasons causing participants to be uncomfortable in vehicles as passengers. Many of these weather conditions

TABLE 10 Overview of the topics that participants reported feeling uncomfortable with for the automotive engineering students, non-technical adults, and seniors. Group averages greater than 50% are represented with ✓, greater than 60% with ✓✓, greater than 70% with ✓✓✓, greater than 80% with ✓✓✓✓ and greater than 90% with ✓✓✓✓✓. The darker grey is associated with larger averages.

Due to:	Uncomfortable when:	Engin. Students	Adults	Seniors	Avg.
vehicle you are in	the driver is distracted	✓✓✓✓✓	✓✓✓✓✓	✓✓✓✓✓	97%
other vehicles	the driver is distracted	✓✓✓✓✓	✓✓✓✓✓	✓✓✓✓✓	94%
other vehicles	following too closely	✓✓✓✓	✓✓✓✓✓	✓✓✓✓✓	89%
environment	in fog	✓✓✓✓	✓✓✓✓✓	✓✓✓✓✓	88%
vehicle you are in	following too closely	✓✓✓	✓✓✓✓✓	✓✓✓✓	88%
vehicle interior	smells like cigarettes	✓✓✓✓	✓✓✓✓✓	✓✓✓✓	88%
environment	there is ice	✓✓✓✓	✓✓✓✓	✓✓✓✓✓	88%
environment	in heavy rain	✓✓✓✓	✓✓✓✓✓	✓✓✓✓✓	87%
vehicle interior	body odor	✓✓✓✓✓	✓✓✓✓✓	✓✓✓	87%
environment	raining at night	✓✓✓✓	✓✓✓✓	✓✓✓✓✓	84%
vehicle interior	pet odors	✓✓✓✓✓	✓✓✓✓	✓✓✓	84%
vehicle interior	mystery stains	✓✓✓✓✓	✓✓✓✓	✓✓✓	82%
vehicle interior	leaking window	✓✓✓✓	✓✓✓✓	✓✓✓✓	82%
vehicle temperature	it is too cold	✓✓✓✓	✓✓✓✓	✓✓✓	81%
vehicle temperature	no airflow	✓✓✓✓✓	✓✓	✓✓✓✓	81%
vehicle you are in	maintenance light(s) on	✓✓✓	✓✓✓✓	✓✓✓✓	78%
vehicle you are in	passing a tractor-trailer with two trailers	✓✓✓	✓✓✓✓	✓✓✓	78%
vehicle temperature	it is too warm	✓✓✓	✓✓✓✓	✓✓✓	76%
vehicle interior	food odor	✓✓✓✓	✓✓✓✓	✓✓	76%
environment	in the snow	✓✓✓	✓✓✓✓	✓✓✓	76%
environment	curvy mountain roads	✓✓	✓✓✓✓	✓✓✓	75%
vehicle you are in	warning light(s) on	✓✓	✓✓✓	✓✓✓✓	75%
other vehicles	slows down quickly	✓✓✓	✓✓✓✓	✓✓	74%
vehicle you are in	passing a tractor-trailer	✓✓	✓✓✓✓	✓✓	72%
vehicle you are in	slows down quickly	✓✓	✓✓✓✓	✓✓	72%
vehicle you are in	unable to see out	✓✓✓	✓✓✓	✓✓	71%
environment	in unfamiliar environments	✓✓✓	✓✓✓	✓	65%
vehicle interior	candy wrappers & food crumbs on the seats	✓✓✓✓	✓✓	✓	64%
vehicle interior	long hair on the seats and floor	✓✓✓	✓✓	✓	63%
environment	it is night	✓	✓✓	✓✓	63%
other vehicles	merging	✓	✓✓	✓✓	62%
other vehicles	changing lanes		✓✓✓	✓✓	62%
vehicle interior	pet fur	✓✓✓	✓	✓	61%
environment	in dense traffic		✓✓✓	✓✓✓	59%
other vehicles	passing a tractor-trailer that has two trailers		✓✓✓	✓✓✓	59%
environment	on curvy roads		✓✓✓✓	✓	58%
other vehicles	passing a tractor-trailer		✓✓✓	✓✓	52%
other vehicles	accelerates quickly		✓✓	✓✓	51%
environment	in the rain		✓✓	✓	51%
vehicle you are in	merging		✓	✓	51%
vehicle interior	dust or dirt on the dashboard	✓✓✓			50%
vehicle you are in	accelerates quickly		✓	✓✓	50%
vehicle interior	perfume odor			✓	48%
other vehicles	passing a vehicle		✓✓	✓	47%
vehicle interior	very small like a hatchback		✓✓		47%
vehicle interior	music is too loud			✓✓✓✓	46%
vehicle you are in	is passing a vehicle			✓	38%
vehicle you are in	is changing lanes			✓	34%

Note: Blank cells represent group averages below 50%.

were related to reduced conspicuity levels. Typically, drivers are comfortable driving at night and in the fog [29,30]. That was simply not the case in this study. It is interesting to note that participants rate these environmental conditions to cause so much discomfort since these environmental conditions will continue to be challenges for future autonomous vehicles [31].

When moving beyond the top five items that cause discomfortable in vehicles as well as looking for trends within and between the three groups of participants, the automotive engineering students expressed more discomfort with the topics related to the vehicle's interior than the other two groups, including candy wrappers and food crumbs on the seats, pet fur and dust or dirt on the dashboard. Other topics that made the engineering students feel uncomfortable included mystery stains, body odor and pet odor. For the adults, the smell of cigarettes, riding in a vehicle passing a tractor-trailer, when the vehicle's temperature is too warm, when there is snow, on curvy mountain roads, riding in a vehicle that slows down quickly and traveling on curvy roads caused more discomfort when compared to the other groups. Finally, the seniors showed more discomfort in comparison to the other groups when there is ice, raining at night, the warning lights are on, and when the music is too loud; the loud music may be related to age-related hearing loss [32].

Future autonomous vehicles have the potential to increase rideshare participation [33, 34, 35]. The reliability and flexibility provided by autonomous vehicles can be efficiently deployed in rideshare services. Autonomous vehicles can preemptively anticipate future demand and relocate to better match vehicle supply and travel demand, which helps rideshare service companies to operate efficiently and thereby ensuring passenger convenience [35]. For example, when two passengers share a ride for the morning commute from home to work, timing may align perfectly. If the two passengers' workday unexpectedly ends at vastly different times which would lead to a long wait for one of the individuals, an additional autonomous vehicle can be repositioned to provide convenient times for both individuals. With carpooling, if the two individuals used a traditional, human-driven vehicle, one passenger would have to bear the long wait or request an alternative rideshare service [33].

Though there are benefits for the passengers using future autonomous rideshare services, there are several concerns regarding sharing a ride with strangers. Three of the top ten reasons causing discomfort were related to smells or odors, specifically cigarettes (88%) and body odor (87%). Currently, most individuals own a personal vehicle, but this ownership model is changing with services like Uber and Lyft. With a rideshare model, odors such as cigarettes and body odor may cause even more discomfort to passengers. Rideshare services can be personal, where the individual travels alone or with people they know (e.g., Uber, Lyft), or it can be pooled, where the individual travels with multiple unknown riders (e.g., UberPool, LyftShared). Many passengers who have used pooled rideshare services including LyftShared and UberPool have posted on Twitter about their discomfort with the service [36]. Most of these passengers' comments were based on the inconsiderate behavior of others in the vehicle, violation of personal space, poor hygiene, and/or drunkenness [36,37].

Trusting the rideshare services is directly correlated with trusting the driver as well as other passengers in a pooled rideshare [38,39]. Recommendations to service providers regarding the desire for passengers and the driver to follow social norms, etiquette on cleanliness, hygiene, having a non-smoking environment, as well as having a policy that passengers do not ride if they are ill [36,40]. The other rider preference highlighted in this study was that all three of the groups preferred either medium to large sedans or SUVs, suggesting there may be a reluctance to be a rideshare passenger in small vehicles. Most of the participants did not prefer to sit in the third row in an SUV or middle position between two seats. These findings are helpful for designers and rideshare companies to be able to maximize passenger comfort in future pooled rideshare experience. Other researchers also shared a similar concern related to a reduced level of comfort when sharing a ride if the desired seat location is occupied or if the rider has to sit in a middle seat [41]. Additionally, a rider may feel uncomfortable with more riders in the vehicle [37,42].

Fully autonomous vehicles (SAE Level 5) will eliminate the driving task, making all individuals traveling in those vehicles passengers. In the current study, distracted driving was the leading cause of discomfort for all groups of participants. Fully autonomous vehicles and rideshare services have the potential to contribute to the reduction of human errors and distracted driving due to the elimination of the driver [43]. Since fully/shared autonomous vehicles are not yet available to the mass market, research is needed to understand what potential users of those vehicles will want and need. In order for users to comfortably ride in autonomous vehicles, passengers must trust the vehicle and the technology. Trust plays a significant role in user acceptability of new and innovative technologies including autonomous vehicles. The user's level of trust in the technology is a significant determinant of the acceptance of that technology [44, 45, 46]. Trust with fully autonomous vehicles needs to increase with users of all ages and hopefully this trust will increase over time. Waymo One is a ridesharing service offering fully autonomous rides in the East Valley of Phoenix, Arizona [47]. Waymo launched its Waymo One service in October 2020, and so far, their service has been increasing riders' trust [48].

Following too closely, or tailgating, was the second most common scenarios that caused discomfort for participants, both when the participants was a passenger in a vehicle as well as when other vehicles were following too closely. This finding is consistent with passengers preferring more defensive driving styles as opposed to aggressive driving styles [49]. Further research is needed to determine the appropriate distance between vehicles for different user groups, which may be a key consideration when increasing users' comfort level when riding or being near autonomous vehicle.

Though much of the current autonomous vehicle research involving passengers has revolved around driving style, headway distance, and vehicle maneuvers, many of the topics that were most agreed upon by all participant groups did not involve driving style, but rather were in-vehicle or environmental factors. Sanitation related topics associated with the interior of the vehicle were some of the most highly rated factors causing discomfort. Example of the sanitation concerns include the smell of cigarettes, body odor, pet odor and corresponding mystery stains. It is beneficial for designers and engineers to gather this type of data from a broad range of users to fully understand the obstacles that must be overcome before wide scale adoption of autonomous vehicles.

When considering interior configurations of autonomous vehicles, there are multiple factors to consider. The results from this study suggest that many participants were uncomfortable when not sitting in the front seat. This may be related to visibility, leg room, ease of ingress and egress, etc. Participants also identified environmental factors that caused discomfort across the groups, including reduced visibility such as fog, heavy rain, raining at night, etc. Many participants experience motion sickness, which often relates to visibility [50]. Future autonomous vehicle layouts need to consider the importance of visibility and how to accommodate users who want and often need to see out of the vehicle to minimize motion sickness. Future head up displays, or augmented reality experiences may also maximize visibility in ways which are not possible in vehicles today.

The at-risk driving population includes seniors who are no longer safe to drive due to age-related declines in hearing and vision, and individuals with disabilities, are potential user groups for autonomous vehicles [51,52]. Though the seniors included in this study were able-bodied drivers, who are active they reported the highest level of discomfort with loud music and the noise from open windows. Autonomous vehicle designers and engineers will need to consider users with hearing and visual limitations. However, several studies have shown that the early adopters of autonomous vehicles are young riders while older adults appear to be more hesitant to adopt this new method of transportation [41,53, 54, 55, 56, 57]. Older adults were not comfortable relinquishing control of a vehicle nor did they feel comfortable in a vehicle without a steering wheel and pedals [41]. The results of the current study indicated the same pattern where most participants prefer being the driver, primarily because they want to have control. While fully autonomous vehicles will not include a steering wheel and pedals, passengers may still desire to feel as though they have control; this perceived feeling of control may be a key factor in making users feel comfortable and/or safe. Pooled rideshare services such as shared autonomous vehicles are in their initial design phase, these vehicles have the potential to be designed to address many of the issues seniors identified as causing discomfort in the current study including following too closely and vehicle interior-related topics such as vehicle temperature. A survey conducted in the greater Phoenix metropolitan area, where Waymo service was offered highlighted that all participants, including older adults, preferred autonomous vehicles over conventional vehicles [48]. Participants' ratings related to wait time, travel time, convenience, and comfort with the autonomous vehicle were better than conventional vehicles.

When designing future autonomous vehicles, it will be important to consider current and future trends such as the continued migration to large cities [58]. As population density increases, light, noise, and air pollution typically increases [59]. To escape the city's pollution, some individuals take refuge through activities such as meditation and yoga [60] (e.g., [61]). This trend has expanded to other transportation industries. Airlines now offer guided meditation (e.g.,

[62]) and yoga that passengers can participate in during their flight (e.g., [63]). Shared autonomous vehicles are anticipated to service large urban areas first [34,42]. These vehicles may provide a soothing space where passengers may escape from busy city life while traveling to their destinations.

In addition to providing a soothing environment, the results of this current study suggest that cleanliness, odor-free, airflow, and ideal temperatures are some topics users view as important factors, which may influence their comfort in the vehicle. Therefore, future autonomous vehicles need to consider methods to combat odors and reduce interior air pollution through solutions such as odor-absorbing fabrics (e.g., [64]) and/or air purification (e.g., [65]). Cleanliness of the vehicle's surfaces was identified as a problem, especially stains. Solutions may include self-cleaning or easy to clean fabrics (e.g., [64]) and/or disinfecting UV lights (e.g., [66]). Temperature and airflow were among the factors that caused discomfort among participants in the current study. With the potential to have a diverse population of shared autonomous vehicle users, temperature and airflow settings could vary drastically between users. Temperature and airflow control or customization will be important to maintain individual's comfort (e.g., [67,68]). If a rideshare model is used over a personal ownership model [36], vehicles may need to eliminate odors between customers. Due to the COVID-19 pandemic, passengers may expect shared autonomous vehicles to sanitize themselves after each ride too. To combat noise pollution associated with city environments, noise absorbing materials should be considered (e.g., [69, 70, 71]). Future autonomous vehicles must consider customization and personalization due to the variability between users wants and needs [23].

The results of this study highlight the common discomfort factors, as well as the opinions that differed between the three age groups. Driver distraction and following too closely were common causes of discomfort irrespective of the group, followed by more than 70% of all participants preferred to be a driver. Similarly, weather conditions concerns were common between the groups. As a passenger, seat adjustments were an important cause for discomfort to all three groups of participants.

Several discomfort factors differed in priority between the three age groups. Although discomfort due to the vehicle's interior existed for all groups, the attributes' importance varied. The factors that the most seniors reported causing the discomfort included loud music, vehicle maintenance, and weather conditions, whereas the engineering students' and adults' discomforts were related to odors, and cabin temperatures. This variation in discomfort factors suggest that seniors may prioritize safety factors. The adults preferred riding in medium to large SUVs (50%), whereas engineering students (57.1%) and seniors (40%) preferred a medium to large sedan. Though these differences are interesting to note, further research into various user populations regarding levels of discomfort between technical and non-technical individuals will be important.

While the current study investigated numerous situations in which passengers may feel discomfort, the responses were typically a dichotomous yes or no. Future efforts should build upon this research to take a deeper dive into the most interesting findings using a rating scale to investigate the level of discomfort with each situation to understand the magnitude of discomfort.

While age-related declines are common in seniors, it is unknown if the seniors in this study had any physical, visual or cognitive limitations. Future research should include users with a variety of physical, visual and cognitive limitations to understand how passenger comfort relates to a broad range of functioning. Additionally, future research should explore individuals who are unable to drive as well as those who are nearing driving retirement. Though there were more male participants in the group of engineering students, there were more females in both the adult and senior groups. Future research should explore potential differences based on gender.

The results of this study identified situations that caused discomfort for passengers. Future studies should investigate how the vehicle could communicate with the user and what information is crucial to make the user feel comfortable and safe, especially in situations that are commonly identified as being stressful or uncomfortable.

The participants in this study were recruited from the upstate area of South Carolina. Future studies should explore individuals from different geographical locations and cultures. While this exploratory study used an interview, it was an important first step. This study provides the needed foundation for future large-scale studies.

Conclusions

An exploratory investigation into passenger discomfort in today's vehicles was conducted with three diverse groups of participants including automotive engineering graduate students, non-technical adults, and senior citizens. A broad range of factors including topics relevant to future autonomous vehicles in addition to traditional comfort factors in conventional vehicles were studied. The results on each topic were tallied for each of the three groups of participants. Some of the most common factors that were key influencers of discomfort for all groups were due to the driver (distraction, following too closely), other vehicles on the road (distraction, following too closely), the environment (fog, ice, heavy rain) and the vehicle interior (cigarette smell, body odor). The results of this study highlight the importance of a pleasant vehicle interior on passenger's perception of comfort. Lessons learned from this study can guide and facilitate the development of future autonomous vehicles to maximize the passengers' experience by taking these factors that cause discomfort into account.

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Abbreviations

CDRS - Certified driving rehabilitation specialist

DOT - Department of Transportation

DOE - Department of Energy

HVAC - Heating, ventilation, and air conditioning

HRI - Human-robotic interaction

SAE - Society for Automotive Engineers

Appendix A; Interview questions, topics, and response types from the interview adapted from our lab's previous work [24]

Topic	Question	Response type
Driver vs. passenger preference	Do you prefer being the driver or passenger?	Yes / No
		Why? (open-ended)
Discomfort as a passenger	Are you ever uncomfortable when you are a passenger in a vehicle?	Yes / No
		If yes, why? (open-ended)
Discomfort due to sounds	Are you ever uncomfortable due to certain sounds?	Yes / No
		If yes, why? (open-ended)
	Where do the sounds come from?	Multiple choice: inside the vehicle, outside the vehicle, both
	Please explain in detail.	Open-ended
Discomfort not being able to see out	Are you ever uncomfortable riding in a vehicle or public transportation when you can't see out?	Yes / No
		If yes, why? (open-ended)
Motion / car sickness	Do you ever get car sick as a passenger?	Yes / No
	- If yes, what makes you sick?	Open-ended
Discomfort due to the driver	Do you ever feel uncomfortable as a passenger when the vehicle: - accelerates quickly, - decelerates or slows down quickly, - is changing lanes, - is merging, - is passing a vehicle, - is passing a tractor-trailer(18-wheeler), - is passing a tractor-trailer that has two trailers (one 18-wheeler pulling two trailers), - is following too closely, - when the driver is distracted, - has a pet in it, - has a child under the age of 5 in it, - other	Yes / No
Poor driver	When you are riding with someone you consider to be a poor driver, what makes you uncomfortable or nervous about their driving?	Open-ended
Discomfort due to other vehicles on the road	Do you ever feel uncomfortable as a passenger when other vehicles on the road: - accelerates quickly, - decelerates or slows down quickly, - are changing lanes, - are merging, - are passing a vehicle, - are passing a tractor-trailer(18-wheeler), - are passing a tractor-trailer that has two trailers (one 18-wheeler pulling two trailers), - are following too closely, - when the driver is distracted, - have a pet in it, - have a child under the age of 5 in it, - other	Yes / No

Topic	Question	Response type
Discomfort due to the environment	Do you ever feel uncomfortable as a passenger when: - in unfamiliar environments, - at night, - in fog, - in dense traffic, - on empty roads, - on bumpy roads or challenging terrain, - on curvy roads, - on curvy mountain roads, - when there is ice, - in the snow, - in the rain, - in heavy rain, - when it is raining at night - other	Yes / No
Discomfort due to the vehicle	Do you ever feel uncomfortable as a passenger when the vehicle: - is a 15-passenger van, - is a large SUV, - is a sedan, - is very small like a hatchback, - has warning light(s) on, - has maintenance light(s) on, - needs to be vacuumed due to grass or dirt on the floor from shoes, - needs to be vacuumed due to candy wrappers and food crumbs on the seats, - needs to be vacuumed due to long hair on the seats and floor, - needs to be cleaned due to dust or dirt on the dashboard, - needs to be cleaned due to mystery stains, - needs to be cleaned due to pet fur, - needs to be cleaned due to pet odors, - needs to be cleaned due to body odor, - needs to be cleaned due to food odor, - needs to be cleaned due to perfume odor, - smells like cigarettes, - has a leaking window, - other	Yes / No
Discomfort due to temperature or airflow	Do you ever feel uncomfortable when: - the windows are open, - heated seats are on, - cooled seats are on, - the temperature is too warm, - the temperature is too cold, - when there is no airflow, - when the music is too loud, - other	Yes / No

Topic	Question	Response type
Vehicle most comfortable in	What type of vehicle are you most comfortable in?	Multiple choice: small car, medium to large sedan, compact or small SUV/crossover, medium to large SUV, minivan or large SUV with 3 rows, Pick-up truck, full size van, other
Vehicle seating positions that cause discomfort	Do you ever feel uncomfortable as a passenger when sitting in: - the front seat, - the back seat, - the middle position between two seats, - the third row in an SUV or minivan, - backseat in a two-door coupe, - bed of truck, - a seat that is not facing forward, - a seat without a headrest, - other	Yes / No

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