

1 **ASSESSMENT OF SPEED CHOICE DURING HIGH SPEED HORIZONTAL CURVES**
2 **EVALUATING DRIVER FAMILIARITY AND ENGAGEMENT**

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ABSTRACT

One of the most common risk assessment decisions a driver makes is to choose the speed at which to navigate a high-speed turn. Current roadway design practice utilizes driver assessment of perceived comfort to obtain a side friction request that is used to design road curvature. This study repeats a 2005 experiment examining driver perception of curve-taking risk, but with a modified methodology designed to focus on whether a driver changes perceptions over repeated maneuvers, and if the driver's perception of risk changes whether the subject is in control of vehicle's speed. A latent response protocol exposed the subject to a curve never encountered previously, then asked the subject to assess discomfort. A learned response protocol repeated the curves, and allowed subjects to indicate if they wanted to go faster or slower to iterate toward their maximum comfortable speed.

A comparison between the latent and learned response protocols showed no evidence of a learning effect, nor significant changes in speeds assessed as uncomfortable during replications. However, the experiments showed that subjects who were in command of vehicle speed chose slower curve-taking speeds than did subjects who were passengers and were assessing speeds selected by the driver. This difference has implications on the large number of curve-taking experiments conducted that have used passenger assessments alone. As well, these results may inform risk-perception of passengers in automated or autonomous vehicles where passenger-to-driver transitions may occur while the vehicle is in motion.

Keywords: risk perception, horizontal curves, speed selection, driver comfort

1 Introduction

2 One of the most common risk assessment decisions a driver makes is to choose the speed at which to
 3 navigate a high-speed turn, and current roadway design practice utilizes assumptions of the side friction
 4 the driver is likely to request. The design values for side friction factor are based on the comfortable
 5 speeds of passengers driven around horizontal curves. Historically, comfortable speeds are assessed via
 6 experiments in which passengers are driven around horizontal curves at constant speeds and are asked
 7 whether or not they feel comfortable; such experiments date from the 1930's and 1940's but have been
 8 replicated in 2005 by Carol Tan, et al (1), the study repeated in this work.

9 There is a history of measurement of drivers to assess curve-taking speeds. The National Cooperative
 10 Highway Research Program Report 774 titled, *Superelevation Criteria for Sharp Horizontal Curves on*
 11 *Steep Grades*, provides a thorough evaluation of design specifications, recommendations, vehicles dy-
 12 namics simulations, and field studies related to horizontal curves (2). Field studies such as those by
 13 Bonneson (3) and by McFadden and Elefteriadou (4) have evaluated horizontal curve design as well as
 14 provided measures of driver behavior including the magnitude of speed reduction on horizontal curves.
 15 Comfort thresholds for horizontal curve design have also be investigated by Said, et al. for purpose
 16 of evaluating side friction demand (5). The role of perceptual on speed-keeping in curves has been
 17 investigated by authors including Charlton (6) and (7), while inertial cues have been investigated by
 18 Raymond, et. al. (8). A thorough review of the literature prior to 2005 related to side friction factors
 19 for horizontal curve design and their relationships with driver comfort and safety is included in Tan's
 20 thesis, *An Investigation of the Comfortable Lateral Acceleration on Horizontal Curves* (1).

21 The experiments in this study were based on the studies conducted by Tan in her thesis (1), whose pur-
 22 pose was to determine the friction factors corresponding to uncomfortable speeds on horizontal curves and
 23 to determine the safety margin against skidding of those friction factors. Tan conducted an experiment
 24 where participants were passengers in a vehicle as it was driven around horizontal curves. Participants
 25 were asked to indicate when they felt "uncomfortable" by pressing a response button. "Uncomfortable"
 26 was primarily defined as feeling a sideways pitch and a desire to slow down.

27 Several factors were considered in Tan's study which include: wearing a blindfold, wearing a seat belt,
 28 seat position within the vehicle, curve radius, direction of travel, and vehicle speed. Figure 1 provides a
 29 complete description of the treatments that were included in the study. Elements highlighted in green
 30 were included in the current study design, excluding the elements crossed out in red. There were 117
 31 participants included in Tan's study, and each one traversed each curve, speed, and direction at least
 32 three times resulting in a total of 9,582 observations.

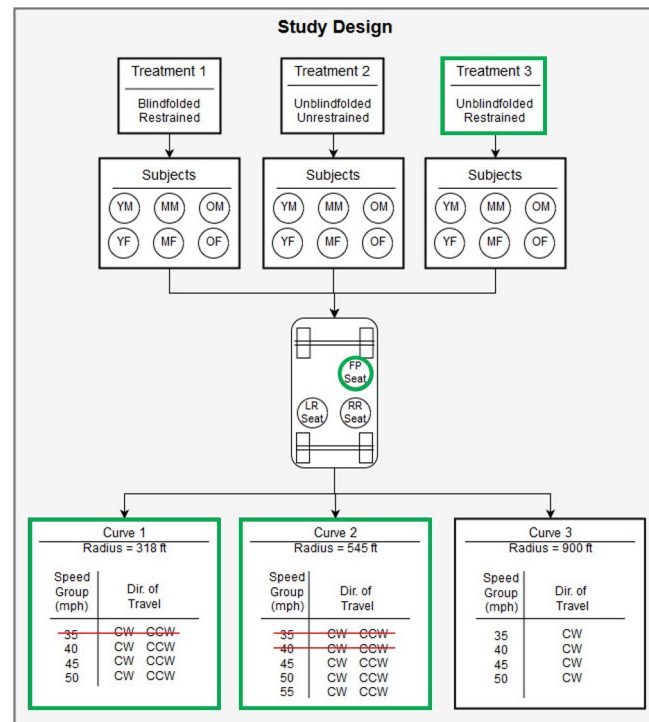


Figure 1 Flowchart of study methodology used by Carol H. Tan in her thesis.

The following are relevant findings from Tan’s thesis (quoted directly):

- As speed increased, the percentage of participants indicating discomfort increased.
- As curve radius increased:
 - The relative frequency of uncomfortable observations by the participant passengers decreased.
 - The differences between test treatments became less apparent.
- For the most part there were no statistical differences between treatments for participant gender.
- Generally, there were no statistical differences between treatments for the different age groups.
- Direction of travel was not statistically significant for any of the experimental treatments.
- The vast majority of uncomfortable passenger participants indicated discomfort before they reached the midpoint of any of the test curves.
- For the smaller radius curve, results indicated that passenger participants based their discomfort on what they “felt” - net lateral acceleration.
- For the curves with large radii, results indicated that passenger participants possibly based their discomfort more on visual cues rather than net lateral acceleration.

The results of Tan’s study have been used to inform current highway design by means of the side friction factors recommended in *A Policy on Geometric Design of Highway and Streets, 2011, 6th* (the AASHTO Green Book) (2, 9). However, there is room to build on Tan’s work to better understand the factors that affect peoples’ selection of comfortable speeds on curves. Specifically, the current study seeks to determine the extent to which selected comfortable speeds depend on prior exposures to a curve. Do drivers learn risk over repeated maneuvers? Is learned risk different from latent risk? Another factor considered in the current study is the method of response. Tan’s study involved a threshold evaluation of comfort – participants were driven at a constant speed and pressed a button if they felt uncomfortable. This study incorporates a limit seeking task – participants continuously choose their maximum comfortable speed throughout the curve.

The proposed methodology partitioned the experiment into two parts: the first was designed to assess the subjects’ latent response, and the second was designed to assess their learned response. The latent response protocol applied to the first exposure of an experimental condition to the participant. It consisted of a threshold evaluation of comfort that replicates the methodology of Tan’s experiment. The learned response protocol was a limit seeking task to find the maximum comfortable speed over repeated exposures to a curve by allowing subjects to use brake and throttle pedals to indicate if they wanted to go faster or slower. These pedals were instrumented to alert the driver who responded accordingly.

The remainder of this paper is organized as follows: the experimental methods are provided followed by descriptions of the experimental designs of both the latent and learned response protocols. Next, in the Results section, the latent response protocol results are compared to the results of Tan’s work. This is followed by an analysis of the learned response protocol results which are then compared to both the latent response protocol results and to Tan’s results. Last in the Results section is a discussion of the confounding effects in this study. Finally, the conclusions from this study are summarized.

Experimental Design and Methods

Method

All experiments were conducted at the Larson Institute Test Track which is shown in Figure 2. The test track is a 1-mile long loop that includes two curves and 2 straightaways. The curve data are shown in Table 1. The design speeds in Table 1 were calculated from the curve data provided on the test track plan using Equation 1 which is from the AASHTO Green Book (9):

$$V = \sqrt{15R(f + e)} \quad (1)$$

where, V = design speed (mph), R = radius of curvature (ft), f = specified side friction demand, and e = superelevation (ft/100 ft). The standards for horizontal curves in the AASHTO Green Book were based on an experiment originally conducted in the 1930’s and 1940’s, and is the same as in Tan’s thesis. (1).

The vehicle used for the experiment was the Intelligent Vehicle and Systems Group mapping vehicle, shown in Figure 3. The global position of the vehicle was determined by a military-grade NovAtel DL-4 Differential Global Positioning System (DGPS). Differential corrections were made using a base station



Figure 2 An overview of the Larson Test Track Facility.

Table 1 Curve Parameter Data

Curve	Design Speed (mph [km/h])	Radius (ft [m])	Superelevation (ft/100ft [m/100m])	Curve Length (ft [m])
1	35 (56)	318 (96.4)	0.10	680 (206.1)
2	45 (72)	545 (165.2)	0.11	1720 (521.2)

at the Larson Institute which was calibrated on November 13, 2016. The resulting precision error ($1 - \sigma$) of the Differential GPS (DGPS) was 4.6 mm in X, 5.5 mm in Y, and 3.7 mm in Z. The orientation of the vehicle was determined by a Honeywell HG1700 Inertial Measurement Unit (IMU) and a ring-laser gyroscope. The sensor readings were fused through a factory-integrated Extended Kalman Filter (EKF) to provide a state estimate. The sensors were mounted on a ridged frame on the roof of the mapping vehicle which allows for the motion of each sensor to be decoupled from the flex of the vehicle body. A GPS pulse-per-second (PPS) triggering signal was up-sampled to produce a trigger for each sensor, to ensure a common time scale among all of the sensors. The sampling rate used for all of the sensors in this study was 20 Hz.

The participants were seated in the passenger side of the van, seat-belted, and with their view of the speedometer obstructed. The participants' inputs were mediated through a set of Logitech G27 gaming pedals that were located on the floor in front of the passenger seat in the vehicle. These pedals are shown in Figure 4.

An input-to-audio algorithm was developed that interprets pedal commands and uses these to cue the driver via sound to respond accordingly. The audio was delivered to the driver via in-ear headphones such that the participant could not also hear the audio cues to the driver (for safety, the driver only had a headphone in one ear so that he/she could still hear their surroundings). When the participant pressed a pedal, a 0.05 second long beeping sound was emitted repeatedly. The interval in between the beeps varied according to Equation 2:

$$i = 0.5 - 0.95p \quad (2)$$

where i = the interval between the beeps (seconds) and p = the percentage that the pedal is pressed (0 is not pressed, 1 is fully pressed). The throttle and brake pedals were differentiated by the pitch of the sound. The pitch was 500 Hz when the brake was pressed, and 1000 Hz when the throttle was pressed. The waveform of both sounds was a sine wave.

Participants were recruited with the goal to obtain behavioral, demographic, and response variability. The experiment was advertised through the use of flyers posted around the Pennsylvania State University's campus. Upon arrival at the Larson Institute Test Track, participants were welcomed and asked to read and sign a consent form. They were then asked to complete a short form that asked for their age, gender, and driving history. Questions about driving history included number of years driving, average number of hours driven per week, number of vehicle accidents, and time since most recent vehicle



Figure 3 The Intelligent Vehicle and Systems Group mapping vehicle.

1 accident. After completing this form, four anthropometric measurements were taken: height, stature,
 2 seated height, and seated eye height. Participants were then shown to the mapping vehicle and were
 3 given a set of written, step-by-step instructions that described the protocol. All of the experiments were
 4 conducted between 3:30 pm and 7:30 pm and were before sunset. In addition, the road conditions were
 5 always dry.

6
 7 The independent variables involved in all the tests that follow were the curve radius, the vehicle's
 8 speed, and the direction of travel. The curve radii were 318 ft and 545 ft; more details can be found
 9 in Table 1. The test speeds were 40, 45, and 50 mph for the 318 ft radius curve, and 45, 50, and 55
 10 mph for the 545 ft radius curve. These curves are the same curves used as in Tan's study; however, the
 11 largest curve (900 ft radius) in Tan's protocol was excluded from the current protocol because it elicited
 12 a relatively small percentage of uncomfortable responses (1.5%). Additionally, the slowest test speeds
 13 in Tan's protocol for the remaining curves (35 mph on the 318 ft radius curve; 35 mph and 40 mph
 14 on the 545 ft radius curve) were excluded from the current protocol for the same reason (less than 2%
 15 uncomfortable responses for all experimental conditions). The order of the trials for each curve and the
 16 direction of travel were counterbalanced between participants. The speed was selected randomly for all
 17 trials.

18 *Design of the Latent Response Protocol*

19 The latent response protocol was designed to assess a participant's perception of risk for their first
 20 traversal on both of the curves of the test track. Participants sat in the passenger seat of the vehicle as
 21 it was driven at a randomly-chosen value among a selection of test speeds. The vehicle began from rest
 22 at least 200 meters before the entrance to the curve. The driver accelerated to the selected speed before
 23 entering the curve and used cruise control to maintain that speed through the curve. The participants
 24 were asked to indicate when they felt uncomfortable by pressing a brake pedal that was instrumented to
 25 alert the driver. "Uncomfortable" was defined as a desire to slow down. If the participant pressed the
 26 brake pedal, the driver slowed the vehicle to a stop to end the trial.

27
 28 The dependent variable was the binary response of the participant that indicated whether or not they
 29 felt uncomfortable at any point while traversing the curve. In the current protocol, participants indicated
 30 discomfort by pressing a brake pedal. This is in contrast to Tan's experiment where participants indi-
 31 cated discomfort by pressing a hand-held button. It was assumed that the different response methods
 32 between the protocols would not significantly impact the response behavior. Furthermore, the brake
 33 pedal was preferred for the current protocol because it was also used in the learned response protocol.
 34 The hypothesis proposed for this experiment was that participants would tend to indicate discomfort at
 35 slower speeds when traversing unfamiliar curves.



Figure 4 G27 Gaming Pedals that were used to mediate participants' inputs.

Design of the Learned Response Protocol

The learned response protocol was designed to quantify the participants' perception of risk over successive traversals of a curve. Participants sat in the passenger seat of the vehicle and were instructed to use the throttle and brake pedals at their feet, obtained from a gaming console, as if they had control over the vehicle. The participants were told the following exact phrase: "we are looking for the highest speed at which you feel comfortable". The driver interpreted the participants' inputs via the input-to-audio algorithm and attempted to match the vehicle's pedals to the participants' inputs. This protocol took place after the participant had completed the latent response protocol for both curves. Between the latent response and learned response protocols, participants were provided a 5-minute practice period on the Vehicle Handling Area of the test track where they could become familiar with using the gaming pedals to control the vehicle's speed.

As before, the independent variables were the curve radius, the direction of travel, and the vehicle's initial condition. The curve radii were the same as described in Table 1, and the directions of travel were either clockwise or counterclockwise. The initial condition refers to whether the vehicle was at rest or travelling at high speed before the driver began accepting the pedal inputs from the participant. When the vehicle began from rest, the starting location was at least 200 meters before the entrance of the curve. For the high-speed initial condition, the vehicle began about 500 meters before the entrance of the curve and the driver accelerated the vehicle to 55 mph. At about 200 meters before the entrance of the curve, after the vehicle had reached 55 mph, the driver began accepting inputs from the participant. The participants were notified that "control" of the pedals had been transitioned to them by the driver pressing a button on the dashboard which began the recording of the vehicle's sensors. Participants were instructed that until they pressed the pedals after control had been transitioned to them, the driver would maintain the vehicle's speed. The purpose for including the initial condition as a factor was to evaluate whether a participant chose the same maximum comfortable speed for when they were entering a curve both below or above their comfortable speed. A finding that the initial condition was not significant would increase confidence that the resulting speed for a participant accurately reflects their maximum comfortable speed.

The independent variables – curve radii, direction of travel, and initial condition – were applied in a 2^{3-1} fractional factorial design. Each participant completed three replicates of each treatment combination in the fractional factorial design for a total of 12 trials of the learned response protocol. The order of these 12 trials was randomized for each participant. The generator for the fractional factorial design ($I = ABC$ versus $I = -ABC$) was counterbalanced between participants.

The dependent variable was the vehicle's average longitudinal speed while on the curve. Additional

variables were recorded/calculated that include the vehicle's position, yaw rate, and standard deviation of lateral position. These variables were included to determine whether they had a significant influence on the participants' perception of risk.

An important element in the learned response protocol was the driver's ability to match the participants' pedal inputs using the input-to-audio algorithm. Because the pedal position was communicated to the driver via audio signals, it was impossible for the driver to know the participants' pedal position exactly. Instead, the input-to-audio algorithm was designed to make it easy for the driver to notice changes in the pedal position. This design was found to be the most effective according to subjective evaluation by the research team. The driver underwent hours of practice with the system to develop a practiced and consistent response to the passenger's desired pedal input.

The driver also had to consider the maximum speed at which he/she was willing to traverse the curve. It was expected that since the driver had spent hours driving around the test track at high speeds, that he/she would be willing and capable of handling the vehicle at higher speeds than desired by any of the participants. However, to account for exceptions to this expectation, upper limits were imposed for each curve that the driver would not exceed. These limits were 55 mph for the 318 ft radius curve and 60 mph for the 545 ft radius curve. Participants were not told of these limits before the experiment so as to not influence their expectation that the driver would always match the participant's pedal inputs.

Results

A total of 28 participants were included in this study. Of these, 3 are excluded as outliers based on their heavy use of the throttle during the learned response protocol, where participants used the pedals to indicate their desired speed. It was apparent that several participants held the throttle completely down for the entire duration of several trials. The chosen exclusion criterion is that any participant who held the throttle completely down for any single entire trial should not be included in the analysis. This criterion was chosen because for a trial where the participant holds down the throttle, the vehicle's speed is limited by safety limit imposed on the experimental protocol rather than the participant's perception of risk.

Of the remaining 25 participants included in the study the average age was 26.8 years and the gender distribution was 12 men and 13 women. Nearly all of the participants were in the 20-30 age range due to the fact that participants were mostly students recruited from the Pennsylvania State University campus.

Comparison of the Latent Response Protocol Results to Tan's Work

Figures 5 and 6 show the percent of uncomfortable observations and 95% confidence intervals for the vehicle travel variables alongside the corresponding results from Tan's study. The 95% percent confidence intervals are calculated by treating the observations as binomial trials, and are found using the Clopper-Pearson method of calculating confidence intervals for a binomial distribution. Under two conditions for the current study the percent of uncomfortable observations is zero. However, this can be explained by the limited number of observations ($n < 5$) for those conditions.

There was no statistically significant difference in the percent uncomfortable responses between directions of travel at $\alpha = 0.01$, using a chi-square analysis (318 ft radius curve: $\chi^2 = 0.16$, $p = 0.689$; 545 ft radius curve: $\chi^2 = 0.33$, $p = 0.568$). The same analysis for Tan's study also found no significant difference between travel directions. Although direction of travel was not significant in either study, Figure 5 provides further opportunity for investigation. On the 318 ft radius curve the percent uncomfortable responses in both directions is similar to that of Tan's study. This is not true for the 545 ft radius curve, where the percent of uncomfortable responses for both directions of travel are greater than in Tan's study. In addition, the differences between directions of travel are smaller in Tan's study than in the current study. This is likely due to the significantly smaller number of observations in the current study than in Tan's study. The relatively large confidence intervals for the current study also reflect the more limited number of observations.

A trend where the percent uncomfortable responses increase with speed is present in the results of both the current study and Tan's study. These trends can be seen in Figure 6, but the trend is less clear for the current study than for Tan's. This difference can be attributed to the limited number of observations in the current study.

The percent uncomfortable responses were tested for significance between levels of several categorical variables – direction of travel, trial order, and gender. As discussed previously, a chi-square test found no significant difference between directions of travel – the same result found for Tan's study. To test for significance in the trial order (response on trial 1 versus trial 2) a McNemar test was used instead of chi-square. This is because the chi-square test assumes that the observations between variables are

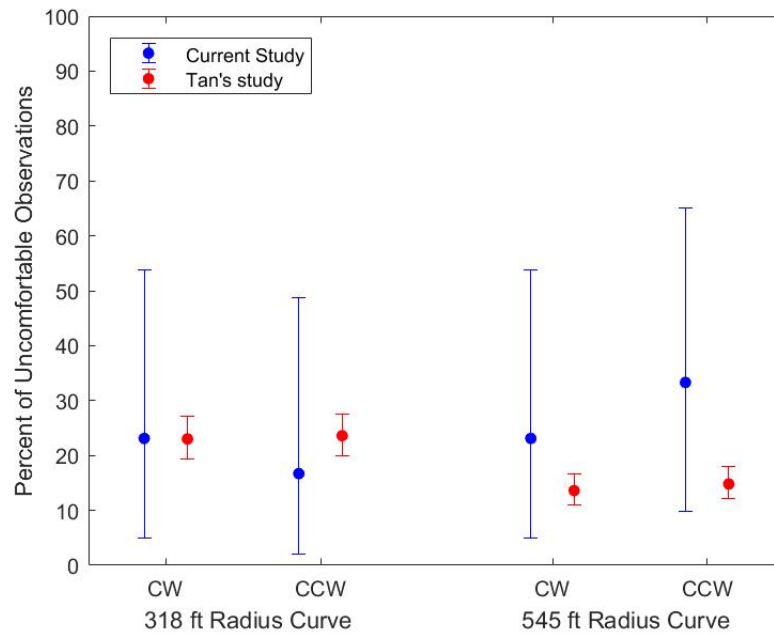


Figure 5 Comparison of the percent of uncomfortable observations and 95% confidence intervals between directions of travel in the latent response protocol and in Tan's study.

independent which is not true for the trial order. The McNemar tests for consistency in responses across two variables (10). The results of the McNemar test show that the trial order is not significant, suggesting that there is no learning effect within the latent response protocol ($\chi^2 = 0.167, p = 0.683$). Lastly, a chi-square test was used to check for the independence between gender and the frequency of uncomfortable responses. The results of the chi-square test found no significant difference between genders ($\chi^2 = 0.254, p = 0.615$) – the same results as in Tan's study.

Analysis of the Learned Response Protocol Results

The direction of travel does not appear to affect the average maximum comfortable speeds selected by participants. Figure 7 shows the average, 5th, and 95th percentile user-selected speeds for opposing directions on the 318 ft radius curve, when starting from rest. The red and green bar across the bottom of the figure represents the results of a 2 sample t-Test between the speed distributions for each direction of travel at every 0.5 meter station coordinate increment at the 5% significance level. It can be seen that the speeds for each direction of travel are not significantly different at any location between the curve boundaries. A similar result was found for the other treatment combinations, indicating that the participants' desired speed is statistically independent of the direction of travel.

A comparison of the average speeds for the different initial conditions shows that the speeds converge to a common distribution that is independent of the curve entry speed. Figure 8 shows an example comparison of the average speeds between initial conditions for one of the treatment combinations – the 318 ft radius curve travelling in the clockwise direction. A two sample t-Test at every 0.5 meter station increment shows that the speed distributions for the different initial conditions are significantly different for an initial portion of the curve, and are not significantly different thereafter. This same pattern is present for the other treatment combinations of curve radii and directions of travel which provides evidence that there is likely a fixed speed that participants are seeking, and this speed is independent of the approach speed.

The average trial speeds were analyzed for statistical significance between factors using a mixed effects model in Minitab. The response variable is the average speed of a trial after the initial condition convergence locations. The fixed factors include the curve radius, direction of travel, and initial condition. Participant were included as a random factor. The experimental design included 3 replications of one half of a 2^{3-1} fractional factorial design for a total of 12 trials per participant, which for 25 participants totals 300 observations. Two of the trials were not recorded due to sensor failures and 10 of the trials were protocol errors (performing the incorrect treatment combination). These 12 trials were not included

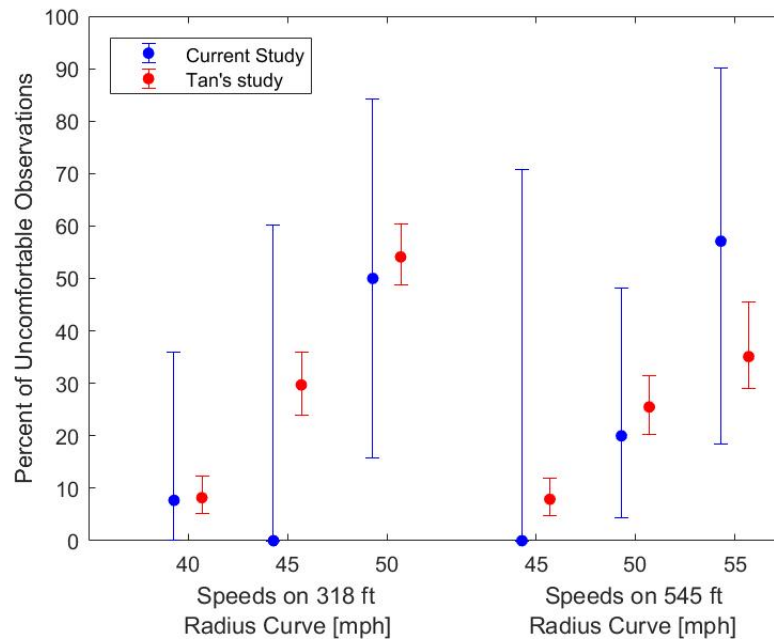


Figure 6 Comparison of the percent of uncomfortable observations and 95% confidence intervals among speed groups in the latent response protocol and in Tan's study.

in the analysis.

The trial number (1-12) and replication number (1-3) were each included as random factors in separate analyses to determine if there was a learning effect. Neither one was found to be significant at the 5% significance level (trial number: $Z = 0.67$, $p = 0.251$; replication number $Z = 0.81$, $p = .209$). Figure 9 shows box plots of the average trial speed separated by trial number and replication number. The failure to find a learning effect makes it possible to average replications of a treatment combination for each subject in order to gain back degrees of freedom for an analysis of the fixed effects. This follow-up analysis included one observation for each of the 4 treatment combinations completed by a participant for a total of 100 observation among all participants.

In the analysis of the averaged replications, only the curve radius and initial condition main effects were found to be significant at the 5% significance level (curve radius: $F = 203.11$, $p < 0.001$; initial condition: $F = 5.46$, $p = 0.022$). Direction of travel and all of the second order effects were not significant (direction: $F = 2.03$, $p = 0.159$; curve*initial condition: $F = 0.15$, $p = 0.700$; curve*direction: $F = 0.02$, $p = 0.890$; direction*initial condition: $F = 1.99$, $p = 0.163$). From Figures 7 and 8 it was expected that direction of travel and initial condition did not significantly affect speed selection. The failure to find this result for initial condition in the mixed effect analysis may be due to the determination of the initial condition convergence locations. The definitions of when the distributions converge is a statistical setting chosen to be 5% in this work; different settings for significance may change the definition, and thus would affect the data used for the averaging.

Comparison Between Latent and Learned Response Protocols

A comparison between the latent and learned response protocols showed no evidence that familiarity with a curve affects the comfortable speed choice. The comparison is based on whether or not the participants were uncomfortable in the latent response protocol, and if they chose a higher or lower average speed in the learned response protocol than the randomly selected speed in the latent response protocol. This creates four categories of possible behavior:

1. The participant indicated that they were **uncomfortable** in the latent response protocol at one of the randomly-selected speeds, then chose an average speed in the learned response protocol that was **greater** than the speed in the latent response protocol.
2. The participant indicated that they were **uncomfortable** in the latent response protocol at one of the randomly-selected speeds, then chose an average speed in the learned response protocol that was **less** than the speed in the latent response protocol.

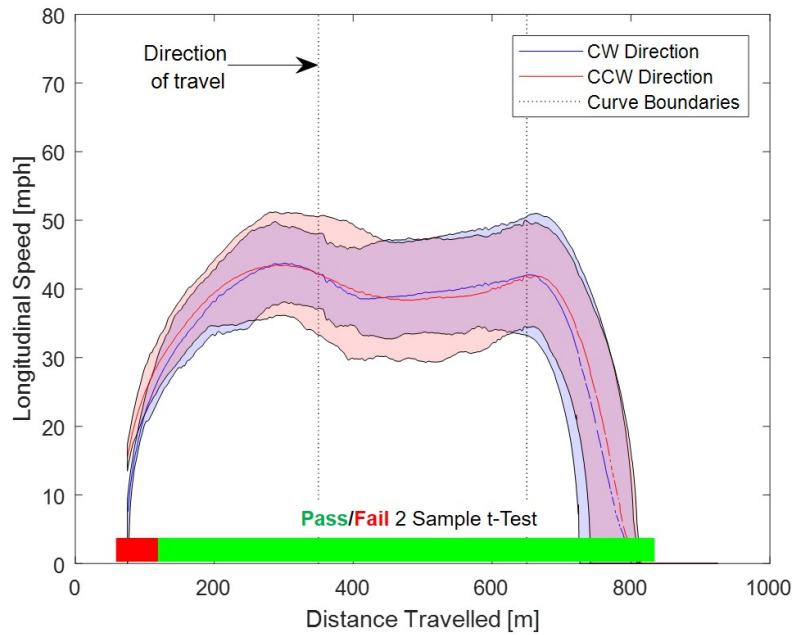


Figure 7 The average, 5th, and 95th percentile speed of all participants for opposing directions of travel on the 318 ft radius curve, when starting from rest. The 2 sample t-Test compares the speed distributions for opposing directions at every 0.5 meter station increment at the 5% significance level.

- 1 3. The participant indicated that they were **comfortable** in the latent response protocol at one of
- 2 the randomly-selected speeds, then chose an average speed in the learned response protocol that
- 3 was **greater** than the speed in the latent response protocol.
- 4 4. The participant indicated that they were **comfortable** in the latent response protocol at one of
- 5 the randomly-selected speeds, then chose an average speed in the learned response protocol that
- 6 was **less** than the speed in the latent response protocol.

7 Categories 2 and 3 are expected behavior – the participant is choosing a speed in the learned response
 8 protocol that agrees with their response in the latent response protocol. Category 1 is indicative of a
 9 learning effect – the participant becomes more comfortable traversing the curve with more exposures,
 10 and therefore chooses a maximum comfortable speed in the learned response protocol that is greater than
 11 the speed in the latent response protocol, i.e. possibly due to greater comfort/experience allowing higher
 12 speeds. Lastly, Category 4 is an anti-learning behavior and has three potential explanations: 1) the
 13 participant was not consistent in their response, 2) there is statistical variation that causes a perceived
 14 discrepancy, or 3) the two protocols do not measure the same psychological response – i.e. there are one
 15 or more factors that affect speed selection in one protocol that aren't present in the other protocol.

16 Figure 10 summarizes the number of participants that fell into each category for either of the curve
 17 radii. For both curves, none of the participants fell into Category 1, which is the category that is
 18 indicative of a learning effect. However, Category 4 included 18 of 25 participants on the 318 ft radius
 19 curve and 7 of 25 participants on the 545 ft radius curve. Considering these relatively high participant
 20 counts, the third explanation for Category 4 is the most likely – that the two protocols do not measure
 21 the same psychological response.

22 The change in responses between the latent and learned response protocols can be evaluated using a
 23 binomial test. The decision for a participant to select a speed in the learned response protocol that is
 24 faster or slower than their speed in the latent response protocol can be analyzed with a null hypothesis
 25 that change in behavior is a random variable with equal probability for both outcomes (50%). The
 26 fraction of observations where participants chose a faster relative speed in the learned response protocol
 27 was tested against the null hypothesis of 50%, assuming a binomial distribution (the complementary
 28 fraction, where participants chose a slower relative speed, yields an equivalent test statistic). The test
 29 was repeated for both curves and for both the participants who were comfortable in the latent response
 30 protocol and those who were uncomfortable. The test results showed that for all cases, except partici-
 31 pants who were uncomfortable on the 545 ft radius curve, the fraction of observations that chose faster

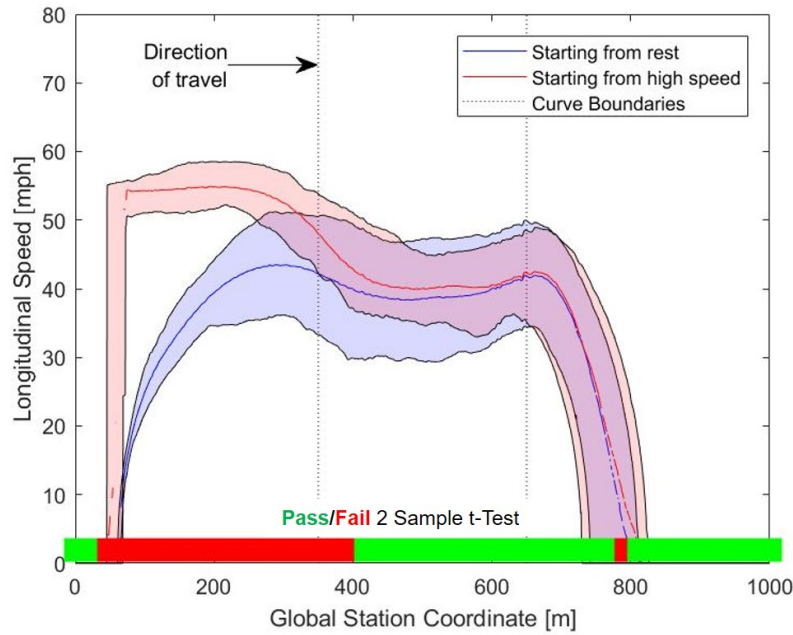


Figure 8 The average, 5th, and 95th percentile speed of all participants for different initial conditions on the 318 ft radius curve travelling in the counterclockwise direction. The 2 sample t-Test compares the speed distributions for opposing initial conditions at every 0.5 meter station increment at the 5% significance level.

relative speeds in the learned response protocol that was significantly different than 50% at the 5% confidence level (318 ft radius curve and uncomfortable: $p = 0.0313$; 318 ft radius curve and comfortable: $p < 0.0001$; 545 ft radius curve and uncomfortable: $p = 0.0078$; 545 ft radius curve and comfortable: $p = 0.2403$). This indicates that for most cases, the probability of a participant choosing a faster relative speed in the learned response protocol is not equivalent to the probability of them choosing a slower relative speed. Therefore, the finding that participants tended to fall into Category 4 behavior, rather than Category 1, is statistically significant for three of the four cases.

Comparison Between Comfortable Speeds for With and Without Control of the Vehicle's Speed

To compare the results of the learned response protocol to Tan's study, the data for each is processed to produce speeds representing percentiles at which the participants were uncomfortable. Table 2 summarizes this comparison. These values, however, have slightly different meanings for either study. Tan's study was based on a threshold evaluation of comfort – participants indicated whether or not they felt uncomfortable at a constant speed through a curve driven by another driver, with no control over their speed. Therefore, the percent uncomfortable speeds from Tan's study are interpolated or extrapolated values that indicate the speeds at which a given percentage of the observations were uncomfortable. The learned response protocol is based on a method of adjustments where participants indicate their desired throttle or brake position to achieve their maximum comfortable speed throughout the curve. The average speeds within the curve boundaries for each trial, separated by curve radius, form two distributions. According to a Lilliefors test, the distribution for the 318 ft radius curve is normally distributed ($p > 0.5$) but the distribution for the 545 ft radius curve is not ($p = 0.0365$). The percent uncomfortable speeds shown in Table 2 are percentiles of these distributions that are calculated assuming normality.

The comparison of the percent uncomfortable speeds in Table 2 shows that the speeds in Tan's protocol (without control of the vehicle's speed) are consistently greater than those in the learned response protocol (with control of the vehicle's speed). This difference is visualized in Figure 11 by fitting normal distributions to the 10th, 50th, and 90th percent uncomfortable speeds in each study. The distributions are not necessarily normally distributed, but this visualization shows clearly that the uncomfortable speeds determined by participants without control of the vehicle's speed (Tan's study) are greater than the uncomfortable speeds determined by participants with control of the vehicle's speed (learned response protocol). A 2-sample t-test between the 10th, 50th, and 90th percent uncomfortable speeds in Tan's study

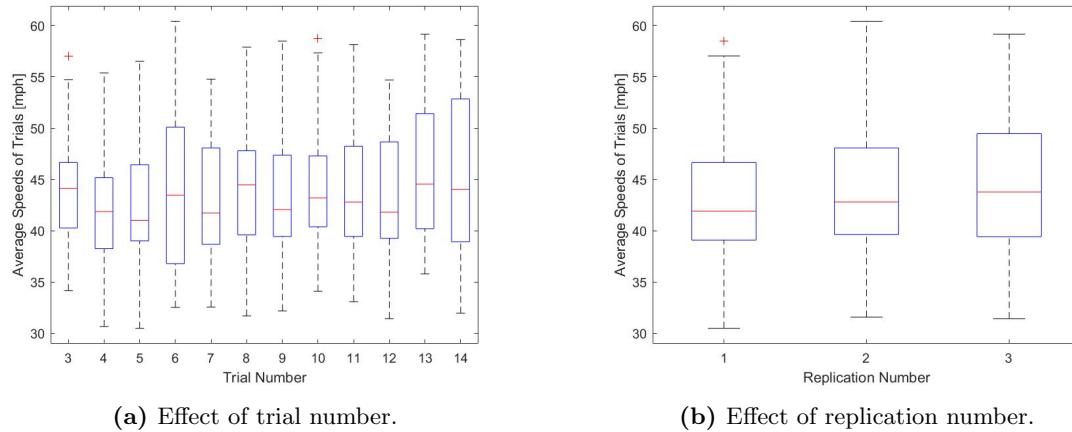


Figure 9 Box plots of the average trial speeds after the initial condition convergence locations, separated by trial number and replication number.

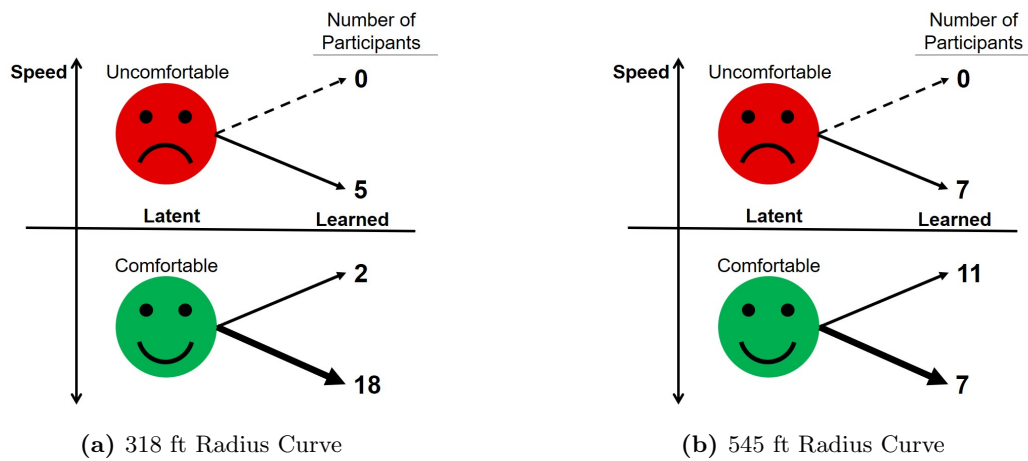


Figure 10 Comparison between the responses in the latent and learned response protocols.

1 and the distribution of average trial speeds in the learned response protocol shows that the distributions
 2 are significantly different at the 5% confidence level for both curves (318 ft radius curve: $p < 0.001$;
 3 545 ft radius curve: $p < 0.001$). There are several possible explanations for the differences between the
 4 results of the two studies:

- 5 • The vehicles in the two studies are different. The vehicle in Tan's study is a 1992 Ford Taurus,
 6 which was 13 years old at the time of the study. The vehicle in the current study is a 1997 Plymouth
 7 Grand Voyager, which was 21 years old at the time of the study. Participants may be exhibiting
 8 more caution when using an older vehicle.
- 9 • The Plymouth Grand Voyager used in this study is a minivan, whereas as the Ford Taurus of
 10 Tan's study is a mid-size sedan. Participants may be obtaining cues from differences in vehicle
 11 dynamics, particularly roll, between these two vehicles. This is supported by the evidence that
 12 different vehicle types affect the measurement of advisory speeds for curves (11).
- 13 • The Plymouth Grand Voyager had problems with its' transmission causing it to lurch as it shifted
 14 gears at low speeds. Participants may be more uncomfortable at higher speeds in a vehicle perceived
 15 to have transmission problems.
- 16 • The decision making processes underlying the two protocols are fundamentally different. The
 17 protocol for Tan's study was a threshold evaluation of comfort, whereas the learned response
 18 protocol in the current study had participants actively seek their maximum comfortable speed. It
 19 is possible that these different methods would yield different results regarding the uncomfortable
 20 speeds for traversing curves. For example, participants in the current study may have felt a greater

sense of responsibility for their own safety because they were “in control” of the vehicle’s speed. They may have therefore been more cautious when choosing their maximum comfortable speed.

This result, that participant control of a vehicle’s speed affects perception of risk, is in agreement with the findings from the comparison between the latent response protocol and the learned response protocol - experiments that used the same vehicle and thus should be equally affected by vehicle-related explanations. That comparison found participants tended to choose slower speeds in the learned response protocol (with control of the vehicle’s speed) than the speeds at which they felt comfortable in the latent response protocol (without control of the vehicle’s speed). The common explanation for both the comparison between Tan’s and the learned response protocol study and the comparison between the latent and learned response protocols is that there may be a fundamental psychological difference between the two response methods that results in different values for the participants’ uncomfortable speed. Participants appear to feel more comfortable at higher speeds when they are not in control of the vehicle’s speed than when they are in control.

The comparisons among the three studies (the latent response protocol, the learned response protocol, and Tan’s study) include several confounding factors that limit the strength of any conclusions drawn. The latent response protocol evaluated only participants’ first exposure to a curve and used the threshold evaluation of comfort. The learned response protocol evaluated participants over repeated exposures to the curves and had participants continuously seek their maximum comfortable speed. Therefore, comparisons between the latent and learned response protocols confound the response method with the learning effect. Tan’s study confounds learning and latent responses, though the large number of replicates for each test subject suggests that the results reflect learned behavior primarily. Comparisons between Tan’s study and the current protocol confound the vehicle type and the driver. Only one driver was used for both the latent and learned response protocols, while several different drivers were used in Tan’s study.

Despite the confounding factors between each study, the effects of learning and of the response methods were consistent across each comparison. There was no evidence of a learning effect found in the comparison between the latent and learned response protocols nor among replications within the learned response protocol. The comparisons between response methods (latent versus learned response protocols and learned response protocol versus Tan’s study) both showed that participants without control of the vehicle’s speed chose faster uncomfortable speeds than when participants had control of the vehicle’s speed. The common results between multiple comparisons suggests that the results are valid despite the confounding factors between individual comparisons.

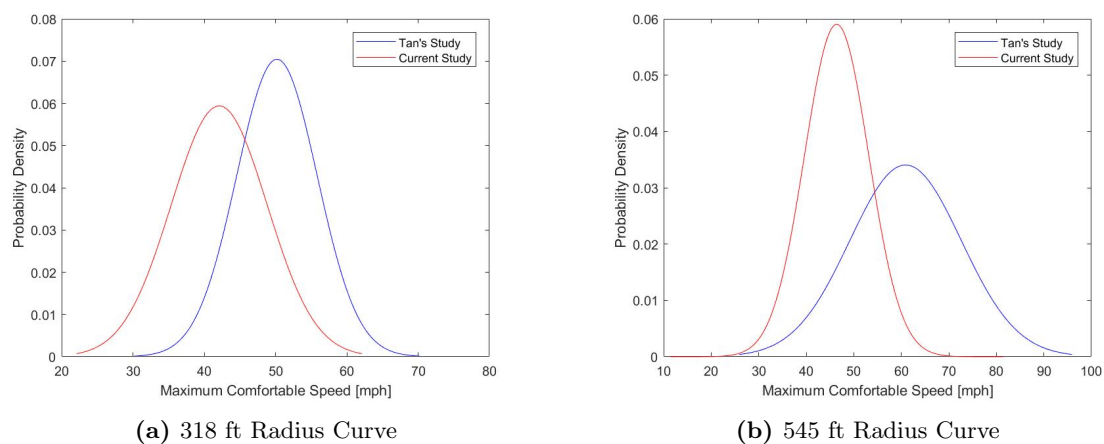


Figure 11 Comparison of normal distributions fit to the 10th, 50th, and 90th percent uncomfortable speeds in each study.

Conclusions

In the latent response protocol, the percent of uncomfortable observations showed similar trends between categorical variables to the trends in Tan’s study.

- The relative frequency of uncomfortable observations increased as speed increased.
- There were relatively fewer uncomfortable observations for the larger radius curve radius than for the smaller radius curve.

Table 2 Comparison of the interpolated and extrapolated 10, 50, and 90 percent uncomfortable speeds from Tan’s study to the corresponding percentile selected speeds of the current study.

Percentile	318 ft Radius Curve			545 ft Radius Curve		
	Speed in Tan’s Study	Speed in Current Study	Percent Difference	Speed in Tan’s Study	Speed in Current Study	Percent Difference
10	42.1	33.2	21.1	47.6	37.8	20.6
50	50.2	42.1	16.1	60.9	46.4	23.8
90	56.6	50.4	11.0	77.6	55.1	29.0

- There were no statistical differences between direction of travel, trial order, or gender.

There was no evidence found of a learning effect when drivers were exposed repeatedly to the same curve and asked to assess risk as they gained familiarity with the curve. Because there was no learning effect, it is reasonable to expect that the initial exposure to a curve – conducted during the latent testing – can be compared to the learning experiments. The selected speeds in the learned response protocol were slower than the corresponding uncomfortable speeds in Tan’s protocol, and also slower than in the latent protocols. The primary variable that consistently explains these differences is the test-subject’s participation: in Tan’s tests and in the latent tests, the participant is simply exposed to someone else’s speed choice – which assumes the driver is more responsible for and comfortable with the traversal speed. But in the learned response protocol, the participant is presented with a speed choice for which only she/he is responsible, and thus may be exercising more caution.

This explanation suggests that risk acceptance appears to be stronger when more than one individual is involved with risk-taking, than when individuals are acting alone. This result could have severe implications for the deployment of autonomous vehicles wherein individuals may treat computer-driven vehicles as trusted drivers. Additionally, this result may require careful consideration of prior risk studies where exposure to risk is being presented to the test subject passively, without means for the subject to control risk. More work is needed to understand perception of risk versus levels of subject control over vehicle inputs.

The driver was a potentially significant confounding variable in both methodologies. It is expected for a passenger’s perception of risk in a vehicle to be influenced by their trust in the driver’s ability and in the driver’s performance. This trust would vary for different participants. Furthermore, the participants’ input method in learned response protocol relied on the driver to respond accurately and precisely to the participants’ desired pedal inputs via the input-to-audio algorithm. Additional experimentation is required to evaluate the driver’s ability to match the pedal inputs of the participants. This could be achieved simply by measuring the driver’s pedal position and comparing it to the participants’ requested pedal position. The instrumentation required to obtain these measurements were not available in the current study. Further investigation is also required to understand the effect, if any, the driver has on the passenger’s perception of risk in terms of trust.

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