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Horizontal Curve Negotiation in Drivers With and Without Autism Spectrum Disorder

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HORIZONTAL CURVE NEGOTIATION IN DRIVERS WITH AND WITHOUT AUTISM SPECTRUM DISORDER

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ABSTRACT

Negotiating horizontal curves is one of the more high-risk tactical control maneuvers when operating a motor vehicle, as drivers must simultaneously and adeptly control their steering adjustment, speed, and lane positioning, as well as accurately perceive the curvature of the road segment and adjust to proprioceptive cues. Given known differences in upper body motor control, coordination, proprioception, and attention, this maneuver may be particularly difficult for drivers with autism spectrum disorder (ASD). The current study examined how drivers with ASD negotiated rural horizontal curves. Thirty-one participants ages 16-30 (13 ASD, 18 TD) drove through a simulated driving environment containing one right and one left horizontal curve, during which vehicle dynamic parameters (i.e., vehicle velocity and acceleration) and steering behaviors (e.g., steering angle, steering velocity, lane positioning, number of lane exceedances, steering reversal rate) were measured. Data were compared relative to whole-curve performance, as well as at different curve segments. Drivers with ASD drove comparably to their TD counterparts with respect to both vehicle dynamic control and steering behaviors when negotiating the first curve. However, when negotiating the second curve, the ASD group had a significantly higher rate of steering reversals and lane exceedances despite spending a similar percent of time out of the lane relative to the TD group. Findings indicate that drivers with ASD follow similar dynamic control profiles to those without ASD. Conversely, steering control profiles differ, especially in more complex scenarios or ones involving unexpected maneuvering. Specifically, drivers with ASD may be less adept at steering recovery, as indicated by a higher rate of steering reversals during curve negotiation. This study adds to the growing literature detailing how drivers with ASD operate motor vehicles. Results corroborate previous work indicating that drivers with ASD excel at following road rules but are more at-risk in complicated driving situations. Findings have the potential to inform targeted driver education protocols for this population, as these data suggest that steering control may be largely implicated in driving differences among those with ASD.

Keywords: autism spectrum disorder, driving, curve negotiation, steering control

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

HORIZONTAL CURVE NEGOTIATION IN DRIVERS WITH AND WITHOUT AUTISM SPECTRUM DISORDER

In the United States, motor vehicle collisions are the leading cause of death for individuals ages 5-24 (Centers for Disease Control and Prevention, 2019), thereby magnifying the importance of understanding the complex integration of cognitive and perceptual-motor abilities required to drive safely. In particular, negotiating horizontal curves is one of the more high-risk tactical control maneuvers when operating a motor vehicle. It is estimated that over 25% of crashes that result in death occur on a horizontal curve (National Academies of Sciences, 2004). The average crash rate for drivers navigating horizontal curves is roughly three times that of other types of roadway segments (National Academies of Sciences, 2004; NHTSA, 2009). The direction of a horizontal curve may also affect its danger and difficulty, as overtaking crashes (i.e., approaching a vehicle from behind and passing it while travelling in the same direction) are more frequent in right curves compared to left (Othman et al., 2009), and individuals drive more quickly through right curves both under normal driving conditions (Othman et al., 2010) and when under the influence of alcohol (Zhang et al., 2014). In addition, horizontal curves may be especially risky for inexperienced adolescent drivers, as inaccurately navigating curves and departing off the road edge is one of the top five crash scenarios among drivers ages 16 to 19 (McDonald et al., 2014; NHTSA, 2008).

When navigating horizontal curves, drivers must simultaneously and adeptly control their steering adjustment, speed, and lane positioning (Fikentscher et al., 2017;

McKnight & Adams, 1970; Reymond et al., 2001), as well as accurately perceive the curvature of the road segment (Campbell et al., 2012) and adjust to proprioceptive cues (Campbell et al., 2012; Reymond et al., 2001). Consequently, driving around curves imposes more attentional demands on the driver (Charlton, 2007), and a breakdown in any one of these processes could contribute to an increased crash risk (McKnight & Adams, 1970). Indeed, the second most common vehicle maneuver involved in fatal crashes is curve negotiation (NHTSA, 2019). The most frequent and fatal type of crash that occurs at horizontal curves is run-off-road crashes, or a single-vehicle crash in which the vehicle leaves the road (National Academies of Sciences, 2004). The most severe and fatal curve-related crashes typically occur on rural roads (National Academies of Sciences, 2004). In Alabama, 60% of fatal crashes occur on rural roads (Alabama Department of Transportation, 2018). Driver errors are the most frequently cited critical reasons for run-off-road crashes, comprising over 95% of cases (NHTSA, 2011). The most commonly cited driver-related crash reasons include internal distraction (i.e., looking at or responding to stimuli within the vehicle), overcompensation, poor directional control, and driving too fast for the curve (NHTSA, 2011), otherwise conceptualized as a failure to control the aforementioned aspects of curve negotiation.

Theoretical Framework for Horizontal Curve Negotiation and Theory

Michon's model of driver behavior (1985) posits that driving is a bottom-up process whose components are hierarchically connected. Three levels are described: (1) a strategic level, wherein an individual decides to drive and therefore plans the stages and goals of their trip (e.g., by choosing a route), (2) a tactical level, which describes a driver's ability to maneuver the vehicle in a controlled manner through various roadway scenarios (e.g., obstacle avoidance, turn-taking, overtaking), and (3) an operational level, which encompasses a driver's ability to operate a vehicle's basic components such as steering, braking, and accelerating. It is important to note that drivers switch from tasks belonging to one level of this hierarchy to another fluidly throughout a drive depending on the roadway environment and changes to the driver's goals. An underlying assumption of this model is that the driver has access to intact cognitive and perceptual-motor faculties such as reaction time, visual perception, motor speed, and hearing.

According to this model, both tactical and operational skills are required to successfully navigate horizontal curves. At the basic operational level, the driver must understand how to steer, brake, and accelerate using the specific control apparatuses of his or her vehicle as they approach the curve. At the tactical level, they must know how to adjust steering, acceleration, and lane positioning in response to perceptual cues at varying segments within the curve. When a driver approaches a curve, they make initial speed adjustments based on what they are able to see of the curve. Once the curve is discovered, the driver determines the curvature of the road ahead, makes additional adjustments to decrease speed, and adjusts their path for curve entry. During curve entry and negotiation, the driver is most concerned with maintaining intended vehicle trajectory and lane positioning via steering control, while continuing to fine-tune vehicle speed based on road curvature and lateral acceleration cues. Last, when exiting the curve, the driver accelerates to the appropriate road speed and readjusts lane positioning (Campbell et al., 2012; McKnight & Adams, 1970). This tactical process has been shown to be difficult to master but improves with experience, as young, inexperienced drivers (25 years and younger) are at a higher risk for adverse events at horizontal curves (Choudhari & Maji, 2019) compared to drivers ages 26 to 50.

Driving simulator studies have attempted to quantify the effects of both internal and external factors on curve driving among drivers. Typically, sharper curves (i.e., curves with a smaller radius) prompt drivers to compensate with slower speed and a larger steering angle (van Winsum & Godthelp, 1996). Sharper curves also lead to higher variability in lane positioning (Jeong & Liu, 2017; van Winsum & Godthelp, 1996). However, both fatigue and cognitive distraction have been shown to impair speed management in curves (Du et al., 2015; Fu et al., 2019). Fatigue also affects steering control and variability in lane positioning (Du et al., 2015). Additionally, among drivers under the influence of alcohol, steering (Li et al., 2019) and speed (Li et al., 2019; Zhang et al., 2014) control decrease around curves. Patient populations also have impaired curve negotiation; for example, drivers with Parkinson's Disease have poorer vehicle control and commit more driving safety errors than typically-developing (TD) controls (Uc et al., 2012).

Driving and ASD

Given the skills required to safely negotiate horizontal curves, this maneuver may be particularly difficult for drivers with autism spectrum disorder (ASD). Diagnostically, ASD is characterized by deficits in social communication and the presence of restricted, repetitive behaviors and interests (APA, 2013). Additionally, general differences in attention (Sinzig et al., 2008) and proprioception (Morris et al., 2015) have been observed. While not currently diagnostic, individuals with ASD have known differences in motor planning (Fabbri-Destro et al., 2009) and coordination (Fournier et al., 2010).

For example, with respect to upper body coordination, individuals with ASD have kinematically atypical, “jerky” arm movements (Cook et al., 2013) and require more time to both initiate and execute contralateral arm movements (Glazebrook et al., 2006).

Indeed, the literature suggests that aspects of tactical and operational driving components may be more challenging for individuals with ASD. Observational driving evaluations of individuals with ASD have shown poorer steering maneuvering and lane maintenance relative to TD individuals (Chee et al., 2017; Classen, Monahan, & Hernandez, 2013). Driving simulator paradigms have indicated that drivers with ASD require more time to master operational driving tasks such as steering and braking (Brooks et al., 2016), commit more steering-specific driving errors (Wade et al., 2017), have more variability in lane positioning (Classen, Monahan, & Wang, 2013; Cox et al., 2016; Cox et al., 2017; Patrick et al., 2018), and have more difficulty regulating speed (Classen, Monahan, & Wang, 2013) relative to TD drivers. Moreover, drivers with ASD experience difficulty controlling vehicle acceleration (Cox et al., 2016), as well as responding to increased cognitive demand in driving situations (Cox et al., 2016; Daly et al., 2014).

However, recent literature suggests that drivers with ASD may be more likely to follow driving rules and exercise explicit caution while driving (Chee et al., 2017; Myers et al., 2021). This is supported by the recent work of Curry and colleagues (2021), whose large retrospective study of driving records indicated that drivers with ASD had lower rates of crashes, moving violations, and license suspensions compared to their TD counterparts. Of note, however, is the fact that, among young drivers involved in a motor vehicle collision, those with ASD are involved in more crash scenarios involving complex maneuvers such as left turns or U-turns (Curry et al., 2021). Naturalistic driving study designs have also shown that novice drivers with ASD have higher variability in lane positioning when maneuvering through turning scenarios such as left turns or roundabouts, indicating poorer vehicle control (Van Zuylen et al., 2020). Taken together, these findings suggest that complex driving scenarios involving turning may be specifically implicated in ASD driving risk.

The Present Study

While it is clear that the skills required to safely navigate curves may be more challenging for individuals with ASD, no study to date has specifically investigated how curve negotiation among these drivers may differ from that of their TD counterparts. The current study examined driving performance during horizontal curve negotiation in a driving simulator environment among drivers with and without ASD. Outcome measures of interest included vehicle dynamic qualities (i.e., vehicle velocity and acceleration) and vehicle steering variables. These variables align with the skills and driver behavior outcomes that are essential to safe curve driving (i.e., maintaining velocity and acceleration within a range that allows for safe vehicle control, controlling steering behavior to maintain safe lane positioning, etc.). Drivers with ASD were expected to have an overall slower speed, as well as higher variability of speed, during whole curve negotiation compared to TD drivers. Furthermore, drivers with ASD were expected to have an overall higher acceleration (i.e., more changes in velocity over time), as well as an overall higher variability in acceleration during curves than TD drivers. It was also expected that drivers with ASD would have higher values for steering metrics (standard deviation [SD] steering angle, mean steering velocity, SD steering velocity, number of steering reversals, steering range, SD of lane positioning, number of lane exceedances, percent time spent out of the lane) compared to TD drivers, thereby indicating poorer steering control.

Given that effective curve negotiation involves employing various tactical stills at different segments of the curve, it was also of interest to explore how velocity, acceleration, and steering behaviors differed at varying curve segments. As prior literature has demonstrated poorer tactical driving abilities among drivers with ASD (Cox et al., 2016) and that drivers with ASD drive more slowly overall (Bishop et al., 2018), it was predicted that ASD drivers would enter and exit curves more slowly than TD drivers. It was also expected that they would decelerate around the apex of the curve and have a higher acceleration at the exit of the curve. Post hoc exploratory analyses were used to examine differences in steering control at varying curve segments, as there is no previous literature to guide these hypotheses.

METHODS

Participants and Recruitment

Twenty participants with ASD and 20 TD participants were recruited for a larger study aimed at understanding the neuropsychological and neural correlates of driving performance and hazard perception among drivers with ASD, attention-deficit/hyperactivity disorder (ADHD) and TD (Bednarz, Kana, et al., 2021; Bednarz, Stavrinos, et al., 2021). TD participants were recruited via posted flyers and advertisements in the community, as well as via a laboratory registry of participants. Participants with ASD were recruited using the same methods, in addition to referrals from various local community clinics and mental health providers. Participants were matched on age, gender, IQ, and years since licensure across groups.

Criteria for inclusion for all participants were as follows: individuals between 16 and 30 years of age with a valid driver's license who had driven independently in the last 30 days, had a corrected visual acuity of 20/40 or better, and had an IQ > 70. Individuals with the following comorbid diagnoses or conditions were excluded from the study: physical disabilities, serious mental health disorders (e.g., schizophrenia, bipolar disorder), seizure disorders, obsessive compulsive disorder, Tourette's syndrome, traumatic brain injury, concussion with loss of consciousness. Additionally, individuals were excluded from the study if they took medications known to affect motor functioning (e.g., anticonvulsants, benzodiazepines), antipsychotic medications, and/or chemotherapy agents. Given that the larger study involved participating in magnetic resonance imaging, individuals were also excluded if they reported having ferromagnetic materials in the body, as well as if they reported comorbid conditions contraindicated for scanner use (e.g., claustrophobia) or if they weighed over 350 lbs.

For inclusion in the ASD group, individuals required a diagnosis of autism spectrum disorder, Asperger's syndrome, autistic disorder, or PDD-NOS given by a medical or psychological professional using DSM-IV (APA, 2000) or DSM-5 (APA, 2013) criteria. The source of diagnosis was based on participant and/or parent report, which was confirmed by diagnostic records provided to the research team. In addition, the Autism Spectrum Quotient (AQ; Baron-Cohen et al., 2001) was administered to confirm the presence of clinically significant symptoms; all participants with ASD had AQ scores ≥ 26.

For inclusion in the TD group, individuals required an AQ score < 26. Individuals were excluded if they reported taking antidepressant or anti-anxiety medications, mood stabilizers, or stimulant medications. In addition, given that the larger study sample included individuals with ADHD, individuals were excluded from the TD group if they affirmed ≥ 4 symptoms on the Adult ADHD Self-Report Scale (ASRS; Hines et al., 2012).

Apparatus

Participants completed a drive in a fully immersive, state-of-the-art, high-fidelity driving simulator (Realtime Technologies, Inc.; see **Figure 1**). The vehicle cab was a 2016 Honda Pilot, which featured a fully functional gearshift, brake, throttle, steering wheel, turn signal/indicator, and dashboard. Three 80 in LCD projection screens provided a 180° field of view to the front and sides of the driver. A screen behind the cab allowed the driver to look in the rear-view mirror and see the simulated environment behind the vehicle. Additional LCD projections displayed in each side mirror. A 5.1 surround sound system (5 full bandwidth channels plus one subwoofer) provided full Doppler effects of ambient traffic. A motion base allowed the vehicle to pitch forward and backward during braking and acceleration. Simulator data were sampled at 60 Hz.

Figure 1. Driving simulator

Driving Simulator Task

Practice Drive

Participants completed an approximately 4.5 mile practice drive to demonstrate their ability to operate the driving simulator and capacity to acclimate to the simulation without simulator sickness, an experience that is more common among older individuals (Brooks et al., 2010). When initialized, a pre-recorded audio clip instructed participants on how to use the simulated vehicle. The initial instructions were to assure the participant knew where the gear shift was, how to use the gear shift (e.g., telling the participant that the "D" stood for "Drive"), and how to use the brakes, gas throttle, steering wheel, and turn signals. A research assistant stood by to answer questions and assure that the participant understood how to operate the vehicle. Once the audio recording stopped, the research assistant asked the participant to drive as they normally would on a real road and to try to drive in the right lane.

During the practice drive, participants drove through a 35 MPH two-lane road with a left curve in the middle of the section, a 70 MPH four-lane freeway with a left curve in the middle of the section, and another 35 MPH two-lane straight road in a daytime fair-weather scenario. On the transitions entering and exiting the freeway section, the participant had to come to a stop to turn onto the next section. No ambient traffic was present in the practice drive.

Experimental Drive

During the driving simulator task, participants navigated 2 residential horizontal curves (1 right curve first, 1 left curve second) on 2-way, 2-lane roads with a radius of approximately 200 m (656.17 ft) and an angle of approximately 60° (see **Figure 2**). The straight section before the curve was about 50 m (164.04 ft), the curve sector was about 414 m (1,358.27 ft), and the straight section after the curve was about 50 m (164.04 ft). Lane width remained constant at 3.5 m (11.48 ft). No ambient traffic was present during residential curve negotiation, and participant driving was uninterrupted by hazards.

The left curve was a mirrored copy of the right curve; this allowed for more rapid and consistent programming of the driving task. Consequently, the driving environments leading up to each curve differed between the first and second curve. The first curve was preceded by a residential neighborhood wherein drivers were confronted with hazards to avoid, while the second curve was preceded by a freeway straightaway.

Measures

Demographics

Participants were asked via telephone screening to provide demographic information including age, gender, race, medication usage, and comorbid diagnoses. Prior to coming into the laboratory, participants completed an electronic questionnaire and provided driving-related information such as date of licensure and average days driven per week.

Figure 2. Example of the right curve approach from the driver's point of view

Eligibility Screening

The Wechsler Abbreviated Scale of Intelligence, 2nd Edition was used to estimate participants' cognitive ability (WASI-II; Wechsler, 2011). A Full-Scale IQ (FSIQ-2) composite score can be calculated by administering one subtest from each domain (Vocabulary and Matrix Reasoning, respectively). Participants were administered the two-subtest WASI-II prior to entering the driving simulator to assure an FSIQ-2 > 70. The WASI-II has been shown to have high concurrent validity with other larger cognitive batteries (correlations between 0.71 and 0.92), and the FSIQ-2 has been shown to have an average reliability coefficient of .94 (McCrimmon & Smith, 2012).

Corrected visual acuity was assessed using a Snellen eye chart. Participants stood 10 feet away from a lightbox display of 9 rows of letters where each subsequent row had an increasing number of letters that decrease in size. Beginning with the fifth row, participants read each line aloud with both eyes open, and continued to read letters on each successive line until they failed to correctly identify at least 50% of the letters on a line. If applicable, participants wore glasses or corrective lenses during the assessment.

ASD Symptomatology

The Autism-Spectrum Quotient (AQ) questionnaire was used to assess the presence of symptoms consistent with ASD (Baron-Cohen et al., 2001). The AQ is a 50-item questionnaire comprised of 5 sets of 10 questions that assesses five different areas of ASD symptomology (social skill, attention switching, attention to detail, communication, and imagination), with higher scores indicating a greater number of ASD symptoms present (Baron-Cohen et al., 2001). Discriminative power tests of the AQ revealed a successful differentiation rate of 80% (Naito et al., 2010).

Driving Simulator Variables

Data were recorded throughout the approximately 510 m of road capturing the approach tangent, horizontal curve, and exit tangent. For analysis, each variable was analyzed considering the entire curve. In an effort to see if curve negotiation metrics differed at curve sections across groups, the curve was also segmented into 6 sections (**Figure 3**): (1) approach tangent, measuring 50 m (164.04 ft), (2) curve entry, measuring 100 m (328.08 ft), and (3) apex entry, measuring 105 m (344.49 ft), (4) apex exit, measuring 105 m (344.49 ft), (5) curve exit, measuring 100 m (328.08 ft), and (6) exit tangent, measuring 50 m (164.04 ft). Numerous studies have created curve segments for analysis (e.g., Chandrasiri et al, 2016; Fu et al., 2019; Zhang et al., 2014), and the number of segments vary widely across studies. Six segments were chosen to mirror the curve sections where changes in speed, acceleration, and steering are likely to occur based on known characteristics of curve driving behavior (McKnight & Adams, 1970).

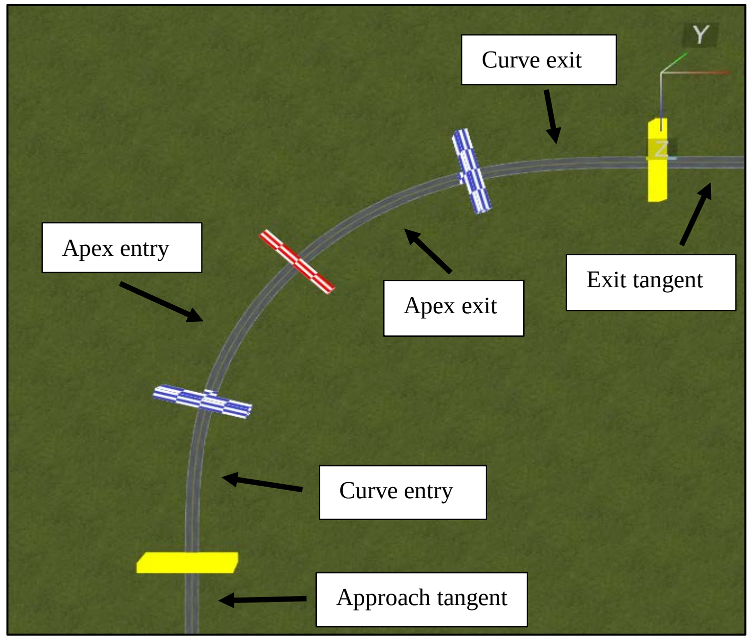


Figure 3. Curve segments

Vehicle Dynamic Variables.

1. Longitudinal Velocity – The magnitude of change in the vehicle's longitudinal position, measured in miles per hour (mph) (Zhang et al., 2014). Both the mean and SD of longitudinal vehicle velocity were calculated.
2. Longitudinal Acceleration – The rate of change of longitudinal velocity over time, measured in mph^2 (Fu et al., 2019). This is a measure of how vehicle speed varies while driving. Both mean and SD values were calculated.

Steering-Related Variables.

1. Steering Angle – The angle of the absolute position of the steering wheel measured in degrees (Li et al., 2019). The value is positive if the steering wheel rotated clockwise, negative if rotated counter-clockwise, and 0 if the wheel is at the absolute 0 point. Of greater interest, however, is the SD of steering angle, where a higher standard deviation of steering angle is an indicator of difficulty maintaining a stable lane position. In addition, this variable will be used to calculate the subsequent three variables.
2. Steering Velocity – The magnitude of change in the steering wheel's position, measured in degrees per second (Li et al., 2019). Higher values denote faster angular movement of the steering wheel. Steady curve negotiation is denoted by relatively small mean values (i.e., slower steering wheel movements), while turning the steering wheel quickly and sharply is denoted by large values. SD of steering velocity reveals the variability in steering speed, another metric of steering control.

3. Number of Steering Reversals – The number of steering direction reversals larger than 5 degrees (Li et al., 2019; Markkula & Engström, 2006). While small adjustments to steering direction are expected to maintain vehicle heading and stability while navigating a curve, larger reversals indicate a need to correct for improper heading or instability. A larger number of steering reversals in a given curve segment indicates less stable steering control.
4. Steering Range – The difference between the maximum and minimum values of steering angle during a given curve segment (Li et al., 2019). Higher values denote larger amplitude oscillations of the steering wheel during curve negotiation, which implies less controlled steering and handling.
5. Lane Positioning – The distance (in ft) between the center of the vehicle and the right lane line (Zhang et al., 2014). A value of 0 would denote that the driver was driving perfectly in the center of the lane. High values mean a tendency to travel toward the left of the lane. Average lane positioning reveals the overall tendency of a participant to drive toward the left or right side of the lane. Of greater interest, however, is the SD of lane positioning (SDLP), which reveals the extent to which a driver is able to control lateral lane positioning using driver control inputs (i.e., the steering wheel). Higher values denote greater variability in steering wheel movement and, by extension, lane positioning.
6. Number of Lane Exceedances – The number of times a vehicle departed from the lane, calculated as when the absolute value of the lateral lane position was > 1 ft (Li et al., 2019). This variable is expressed as a discrete count (i.e., the number of times a participant departed from the lane), as well as a percent frequency (i.e.,

the percentage of time spent in the curve that a participant exceeded the lane boundaries). Higher values and percentages reveal difficulty maintaining vehicle heading and steering wheel control.

Covariates

Driving exposure has been found to affect driving performance, especially among young drivers (Day et al., 2018). Driving exposure was measured as the number of months since licensure and weekly time spent driving. In Alabama, drivers can obtain a license at as early as 16 years old; however, drivers are not considered independently licensed until they have completed 6 months of a “restricted” license phase (Alabama Public Health, 2017). Months since licensure was calculated by subtracting the participant’s date of initial licensure from their appointment date. All participants had completed their restricted license phase. Driving exposure was measured as weekly time spent driving, which was a participant-reported estimate of weekly driving time reported in the pre-appointment electronic questionnaire.

Procedure

This study was approved by the UAB Institutional Review Board. All participants signed an informed consent form. For participants under the age of 18, a parent or guardian signed the consent form as well. Prior to entering the driving simulator, participants were administered the WASI-II and a test of far visual acuity using a Snellen Eye chart. After confirming an IQ > 70 and a corrected visual acuity of at least 20/40, participants completed a neuropsychological test battery not reported in the present study. After a brief break, participants entered into the simulator room to begin driving tasks.

Upon entering the vehicle cab, participants were allowed to readjust the car seat position to their comfort. The rearview mirror could also be adjusted. Participants then completed the practice drive. After assuring there were no problems or additional questions, research assistance prepared participants for the experimental drive by instructing them to drive as they normally would in the real world, and in accordance with pre-recorded in-cab messages directing them to turn left or right at certain intersections. Participants were further instructed to drive in the right lane; pre-recorded audio intermittently reminded participants of this instruction. Participants subsequently completed the experimental drive. Participants were reimbursed for their time with a $125 prepaid card.

Data Analysis

Preliminary Data Analyses

All analyses were conducted using IBM SPSS Statistics, Version 27.0 (IBM Corp., 2020). Each curve was analyzed separately so that practice effects from previous curve exposure during the practice drive and driving environment differences did not confound results. Mean and frequency distributions were used for continuous and categorical variables, respectively, to describe group demographic characteristics and assess for potential outlying data points. If a participant's data point presented an extreme value (> or < 3 SD beyond that participant's respective group mean), the case was excluded from further analysis.

Prior to analysis, the assumptions of each proposed analysis were tested. Shapiro-Wilk tests were conducted for all continuous variables to determine normality of residual distributions for GLM analyses. In the event that the residuals of continuous variables were not normally distributed, a square root transformation was applied. For repeated-measures analyses of variance (RM-ANOVA), data were analyzed both with and without driving exposure variables as covariates in order to determine the extent to which driving experience may serve as a competing hypothesis for group differences. For Generalized Estimating Equations (GEE) with Poisson distributions, the Quasi-likelihood under Independence Model Criterion (QIC) was used to choose the most appropriate correlation structure, while the Corrected Quasi-likelihood under Independence Model Criterion (QICC) was used to determine best model fit (i.e., determine to include or exclude covariates in the model). Additionally, when the RM-ANOVA assumption of sphericity was not met, a Huynh-Feldt correction was applied. When appropriate, Bonferroni-Holm step-down procedure was applied for multiple comparisons.

Given that there were 6 continuous steering-related variables (SD steering angle, mean steering velocity, SD steering velocity, steering range, SDLP, percent of time spent out of the lane), a principal component analysis (PCA) was conducted to reduce the data. Data were converted from wide to long format in order to capture both subject differences and differences in variability among segments and curves. No rotation was applied. Extracted factor scores were used as the dependent variables for subsequent RM-ANOVAs to test hypotheses involving steering behavior variables. As the 2 count variables (i.e., number of steering reversals and number of lane exceedances) distorted the factors generated from the PCA, these were omitted from the data reduction analysis and analyzed independently.

Primary Analyses by Aim

Specific Aim 1: Compare How Vehicle Dynamic Profiles and Steering Behaviors Differ During Curve Negotiation Between ASD and TD Drivers.

***Vehicle Dynamic Hypotheses*.** A 2 (Group: ASD, TD) x 6 (Curve Segment: approach tangent, curve entry, apex entry, apex exit, curve exit, exit tangent) RM-ANOVA was conducted for each curve for each of the vehicle dynamics-related dependent variables (mean velocity, standard deviation of velocity, mean acceleration, standard deviation of acceleration). The between-group effects of these RM-ANOVAs revealed group differences in these variables across the entire curve.

***Steering Behavior Hypotheses*.** A 2 (Group) x 6 (Curve Segment) RM-ANOVA was conducted for each curve using extracted steering behavior factor scores as dependent variables. The between-group effects revealed group differences in these constructs across the entire curve. GEE using a Poisson distribution in calculating risk ratios (RR) was utilized to calculate the group differences in count-based performance outcomes (i.e., number of lane exceedances and number of steering reversals).

Specific Aim 2: Quantify Differences in Vehicle Dynamic Profiles and Steering Behaviors at Different Curve Segments Between ASD and TD Drivers.

***Vehicle Dynamic Hypotheses*.** A 2 (Group) x 6 (Curve Segment) RM-ANOVA was conducted for each curve for each of the vehicle dynamics-related dependent variables. The Group x Curve Segment interaction effects revealed group differences in these constructs at each segment, and follow-up comparisons revealed the nature of these differences.

Steering Behavior Hypotheses. A 2 (Group) x 6 (Curve Segment) RM-ANOVA was conducted for each curve using extracted steering behavior factor scores as dependent variables. The Group x Curve Segment interaction effects revealed group differences in these constructs at each segment, and follow-up comparisons revealed the nature of these differences. GEE using a Poisson distribution in calculating RR were utilized to calculate the association between Group and Segment and count-based performance outcomes. Curve segments were dummy coded to analyze contrasts of interest: (1) comparing performance during the first half of the curve to the second half of the curve (i.e., segments 1-3 vs. segments 4-6); and (2) comparing performance at the curve apex to all other segments (i.e., segments 3-4 vs. all other segments).

RESULTS

Preliminary Data Analyses

Participant Characteristics

All participants passed the vision screening prior to completing the experimental drive. Of the 40 original participants, data from 9 participants were omitted from analysis. Three participants (1 TD, 2 ASD) experienced simulator sickness during the experimental drive, and 1 TD participant's data did not sync properly after collection. Further, 5 participants with ASD held comorbid diagnoses of ADHD. As this study aimed to compare driving performance between drivers with and without ASD, inclusion of participants with a comorbid neurodevelopmental disorder would complicate conclusions drawn from significant results. Demographic information for the final sample can be found in **Tables 1** and **2**.

On average, it took participants with ASD 24.36 sec to negotiate the right curve, and 24.24 sec to negotiate the left curve. TD participants took 23.81 sec to negotiate the right curve, and 24.09 sec to negotiate the left curve. These durations did not significantly differ across groups (all $p > .05$). Descriptive statistics for continuous dependent variables can be found in **Table 3**. Frequency distributions and prevalence rates of count variables can be found in **Table 4**

Table 1

Participant Demographics

Baseline Characteristic	ASD		TD		*t* or χ^2	*p*
	M	*SD*	*M*	*SD*		
Age (Years)	19.77	2.22	20.17	3.14	$t(29) = -.39$	.70
Time Since Licensure (Months)	24.24	22.48	37.67	39.98	$t(29) = -1.09$	.29
Days Driven Per Week	5.07	1.71	5.72	1.84	$t(29) = -.99$	.33
IQ	109.08	21.52	103.72	10.92	$t(29) = .91$	.37
AQ Score	33.38	8.25	14.78	5.00	$t(29) = 7.81$	<.001***
	n	%	*n*	%		
Gender (Male)	7	53.8	12	66.7	$\chi^2(1) = .52$	.47
Race (White)	9	69.2	11	61.1	$\chi^2(1) = .22$	.64

Note. $N_{ASD} = 13$, $N_{TD} = 18$. IQ = intelligence quotient; AQ = Autism Spectrum Quotient.

***$p < .001$

Table 2

Participant Medications and Comorbid Diagnoses

	ASD	TD
Comorbid Diagnoses	Depression: *n* = 3 Anxiety: *n* = 3 Gastrointestinal condition: *n* = 2 Sleep disorder: *n* = 1	Cardiac condition: *n* = 1

Medication Usage	Antidepressant
	  SSRI: *n* =3
	  NDRI: *n* = 1
	Attention
	  SNRI: *n* = 1
	Anxiety
	  Serotonin 5-HT agonist: *n* = 1
	Gastrointestinal
	  Proton pump inhibitor: *n* = 2
	Asthma
	  Inhaler: *n* = 3
	Allergies
	  Antihistamine: *n* = 3
	  Steroid: *n* = 2
		None

Note. N_{ASD} = 13, N_{TD} = 18. SSRI = selective serotonin reuptake inhibitor; NDRI = norepinephrine-dopamine reuptake inhibitor; SNRI = serotonin-norepinephrine reuptake inhibitor

Table 3

Descriptive Statistics of Participant Driving Characteristics

Dependent Variable	1				2				3				4				5				6			
	ASD		TD		ASD		TD		ASD		TD		ASD		TD		ASD		TD		ASD		TD	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Right Curve																								
Vehicle Dynamic Variables																								
M Longitudinal Velocity	39.81	4.19	39.84	4.55	41.11	4.76	40.27	4.95	41.75	6.23	42.11	5.51	41.56	6.74	43.29	5.90	42.78	5.78	44.87	5.96	44.56	5.38	47.11	5.02
SD Longitudinal Velocity	0.46	0.37	0.38	0.25	0.697	0.462	0.630	0.317	0.69	0.750	0.61	0.29	0.52	0.47	0.44	0.24	0.89	0.69	0.850	0.63	0.350	0.26	0.43	0.28
M Longitudinal Acceleration	-0.0004	0.0006	-0.0005	0.0006	-0.004	0.002	-0.005	0.002	-0.0007	0.002	-0.0008	0.002	0.0005	0.006	0.0002	0.002	0.006	0.003	0.006	0.003	0.0006	0.002	0.0007	0.001
SD Longitudinal Acceleration	0.002	0.002	0.002	0.001	0.012	0.008	0.01	0.007	0.01	0.006	0.02	0.01	0.02	0.02	0.02	0.01	0.02	0.008	0.02	0.01	0.005	0.002	0.008	0.004
Steering-Related Variables (Raw)																								
SD Steering Angle	1.37	1.01	1.49	1.04	1.45	0.89	1.76	0.87	1.87	1.36	2.23	2.00	2.21	1.56	1.55	0.89	1.47	0.738	1.65	1.07	1.34	2.30	1.15	0.95
M Steering Velocity	2.58	1.48	3.42	2.32	2.22	1.36	2.43	1.04	2.53	1.10	3.81	4.02	3.23	1.21	3.44	2.49	3.00	1.86	3.71	2.88	1.64	2.06	2.90	2.25
SD Steering Velocity	3.42	1.95	3.76	2.12	2.76	1.25	3.42	1.27	3.45	1.00	4.42	3.28	3.89	0.95	4.33	2.62	3.16	0.90	4.28	2.97	1.78	0.70	2.93	1.69
Steering Range	4.35	2.86	4.93	3.46	5.15	3.01	6.17	2.81	6.75	4.08	7.44	5.95	7.88	5.79	5.96	3.36	5.23	3.10	5.65	3.68	4.28	6.44	3.64	3.06
SDLP	0.16	0.12	0.11	0.06	0.52	0.21	0.47	0.26	0.60	0.35	0.53	0.31	0.82	0.52	0.60	0.36	0.74	0.46	0.68	0.39	0.19	0.16	0.19	0.13
Percent of Time Out of Lane	0.28	0.31	0.45	0.29	0.25	0.20	0.29	0.20	0.52	0.42	0.46	0.29	0.53	0.36	0.42	0.30	0.49	0.37	0.63	0.34	0.62	0.44	0.84	0.46
Steering-Related Variables (Composite)																								
Steering Wheel Activity	-0.23	0.09	-0.22	0.11	-0.25	0.07	-0.23	0.06	-0.23	0.05	-0.18	0.16	-0.21	0.05	-0.21	0.11	-0.26	0.06	-0.21	0.14	-0.33	0.03	-0.27	0.10
Lateral Vehicle Movement	-0.89	0.65	-0.61	0.58	-0.25	0.61	-0.24	0.66	0.48	1.16	0.18	0.97	0.98	1.33	0.20	1.03	0.70	1.42	0.70	0.90	0.08	0.85	0.25	0.73
Left Curve																								
Vehicle Dynamic Variables																								
M Longitudinal Velocity	50.12	8.14	51.13	6.50	48.37	7.08	47.99	5.63	46.71	6.60	46.64	4.82	45.87	6.12	46.08	5.00	45.85	4.56	45.73	5.04	46.14	4.18	45.75	5.31
SD Longitudinal Velocity	0.48	0.47	0.81	1.11	0.71	0.63	1.02	0.86	0.64	0.40	0.50	0.28	0.65	0.55	0.46	0.29	0.53	0.60	0.47	0.23	0.28	0.27	0.21	0.14
M Longitudinal Acceleration	0.001	0.0009	0.001	0.001	0.006	0.003	0.007	0.002	0.0006	0.004	-0.0002	0.002	-0.0001	0.003	-0.0003	0.002	-0.008	0.004	-0.007	0.003	-0.003	0.001	-0.002	0.001
SD Longitudinal Acceleration	0.003	0.002	0.004	0.002	0.02	0.01	0.02	0.009	0.02	0.009	0.02	0.01	0.02	0.008	0.02	0.01	0.02	0.009	0.01	0.008	0.008	0.004	0.008	0.004
Steering-Related Variables (Raw)																								
SD Steering Angle	1.21	0.51	2.35	1.81	2.84	1.48	2.97	1.91	3.23	1.54	2.16	1.27	2.44	1.29	2.55	2.21	10.35	22.68	16.35	30.95	18.82	30.08	11.28	22.96
M Steering Velocity	3.17	1.60	7.06	5.70	3.86	1.67	4.63	2.91	4.81	2.67	3.17	1.52	3.51	2.13	3.66	2.73	9.19	14.42	13.28	19.82	29.40	47.30	30.99	56.44
SD Steering Velocity	4.02	2.01	6.87	5.09	4.61	1.62	4.83	1.62	5.54	3.01	3.96	2.00	4.32	2.10	5.09	3.61	14.64	21.94	19.39	27.80	25.23	38.84	35.71	62.38
Steering Range	4.07	1.07	8.51	7.93	8.89	3.93	8.25	3.93	10.90	3.79	6.69	3.88	8.46	4.51	8.04	6.07	34.34	60.46	62.79	103.38	58.30	93.51	65.18	119.28
SDLP	0.11	0.09	0.09	0.06	0.57	0.24	0.59	0.27	0.53	0.23	0.34	0.15	0.59	0.35	0.46	0.22	0.73	0.43	0.65	0.26	0.22	0.14	0.20	0.10
Percent of Time Out of Lane	0.20	0.38	0.35	0.40	0.32	0.27	0.40	0.22	0.53	0.25	0.40	0.35	0.44	0.20	0.51	0.28	0.54	0.26	0.45	0.16	0.40	0.39	0.46	0.39
Steering-Related Variables (Composite)																								
Steering Wheel Activity	-0.22	0.07	-0.07	0.22	-0.15	0.10	-0.15	0.11	-0.11	0.15	-0.17	0.09	-0.17	0.11	-0.15	0.17	0.38	1.34	0.91	2.01	1.20	2.50	1.20	2.78
Lateral Vehicle Movement	-1.04	0.76	-0.88	0.77	0.03	0.79	0.16	0.74	0.24	0.81	-0.16	0.90	0.19	0.90	0.01	0.59	0.67	1.13	0.33	0.75	-0.55	0.65	-0.46	0.84

Note. M = mean, SD = standard deviation, 1 = approach tangent, 2 = curve entry, 3 = apex entry, 4 = apex exit, 5 = curve exit, 6 = exit tangent

Table 4

Frequency Distributions for Count Variables

Dependent Variable	1						2					
	ASD			TD			ASD			TD		
	n	%G	%T	*n*	%G	%T	*n*	%G	%T	*n*	%G	%T
Right Curve												
Number of Steering Reversals												
0	9	69.20	29.03	11	61.10	35.48	8	61.50	25.81	11	61.10	35.48
1	4	30.80	12.90	5	27.80	16.13	5	38.50	16.13	4	22.20	12.90
2	0	-	-	2	11.10	6.45	0	-	-	3	16.70	9.68
3	0	-	-	0	-	-	0	-	-	0	-	-
Count Total	4	-	30.77	9	-	69.23	5	-	33.33	10	-	66.67
Number of Lane Exceedances												
0	7	53.80	22.58	5	27.80	16.13	4	30.80	12.90	4	22.20	12.90
1	6	46.20	19.35	13	72.20	41.94	8	61.50	25.81	11	61.10	35.48
2	0	-	-	0	-	-	1	7.70	3.23	3	16.70	9.68
3	0	-	-	0	-	-	0	-	-	0	-	-
4	0	-	-	0	-	-	0	-	-	0	-	-
5	0	-	-	0	-	-	0	-	-	0	-	-
6	0	-	-	0	-	-	0	-	-	0	-	-
Count Total	6	-	31.58	13	-	68.42	10	-	37.04	17	-	62.96
Left Curve												
Number of Steering Reversals												
0	11	84.60	35.48	10	55.60	32.26	3	23.10	9.68	6	33.30	19.35
1	2	15.40	6.45	5	27.80	16.13	8	61.50	25.81	7	38.90	22.58
2	0	-	-	2	11.10	6.45	1	7.70	3.23	4	22.20	12.90
3	0	-	-	1	5.60	3.23	1	7.70	3.23	1	5.60	3.23
4	0	-	-	0	-	-	0	-	-	0		-
Count Total	2	-	14.29	12	-	85.71	13	-	41.94	18	-	58.06
Number of Lane Exceedances												
0	10	76.90	32.26	10	55.60	32.26	4	30.80	12.90	2	11.10	6.45
1	3	23.10	9.68	8	44.40	25.81	7	53.80	22.58	12	66.70	38.71
2	0	-	-	0	-	-	2	15.40	6.45	4	22.20	12.90
3	0	-	-	0	-	-	0	-	-	0	-	-
Count Total	3	-	27.27	8	-	72.73	11	-	35.48	20	-	64.52

Dependent Variable	3						4					
	ASD			TD			ASD			TD		
	n	%G	%T	*n*	%G	%T	*n*	%G	%T	*n*	%G	%T
Right Curve												
Number of Steering Reversals												
0	8	61.50	25.81	7	38.90	22.58	6	46.20	19.35	10	55.60	32.26
1	3	23.10	9.68	7	38.90	22.58	5	38.50	16.13	6	33.30	19.35
2	1	7.70	3.23	4	22.20	12.90	5	15.40	16.13	1	5.60	3.23
3	1	7.70	3.23	0	-	-	0	-	-	1	5.60	3.23
Count Total	8	-	34.78	15	-	65.22	15	-	57.69	11	-	42.31
Number of Lane Exceedances												
0	1	7.70	3.23	2	11.10	6.45	2	1.40	6.45	3	16.70	9.68
1	6	46.20	19.35	8	44.40	25.81	4	30.80	12.90	11	61.10	35.48
2	4	30.80	12.90	6	33.30	19.35	6	46.20	19.35	3	16.70	9.68
3	1	7.70	3.23	2	11.10	6.45	1	7.70	3.23	1	5.60	3.23
4	0	-	-	0	-	-	0	-	-	0	-	-
5	0	-	-	0	-	-	0	-	-	0	-	-
6	1[a]	7.70	3.23	0	-	-	0	-	-	0	-	-
Count Total	23	-	46.94	26	-	53.06	19	-	48.72	20	-	51.28
Left Curve												
Number of Steering Reversals												
0	0	-	-	8	44.40	25.81	5	38.50	16.13	8	44.40	25.81
1	7	53.80	22.58	7	38.90	22.58	8	61.50	25.81	9	50.00	29.03
2	5	38.50	16.13	3	16.70	9.68	0	-	-	1	5.60	3.23
3	1	7.70	3.23	0	-	-	0	-	-	0	-	-
4	0	-	-	0	-	-	0	-	-	0	-	-
Count Total	20	-	60.61	13	-	39.39	8	-	42.11	11	-	57.89
Number of Lane Exceedances												
0	1	7.70	3.23	6	33.30	19.35	1	7.70	3.23	1	5.60	3.23
1	4	30.80	12.90	5	27.80	16.13	6	46.20	19.35	9	50.00	29.03
2	7	53.80	22.58	5	27.80	16.13	6	46.20	19.35	5	27.80	16.13
3	1	7.70	3.23	2	11.10	6.45	0	-	-	3	16.70	9.68
Count Total	21	-	50.00	21	-	50.00	18	-	39.13	28	-	60.87

Dependent Variable	5						6					
	ASD			TD			ASD			TD		
	n	%G	%T	*n*	%G	%T	*n*	%G	%T	*n*	%G	%T
Right Curve												
Number of Steering Reversals												
0	8	61.50	25.81	11	61.10	35.48	11	84.60	35.48	15	83.30	48.39
1	3	23.10	9.68	5	27.80	16.13	2	15.40	6.45	3	16.70	9.68
2	2	15.40	6.45	2	11.10	6.45	0	-	-	0	-	-
3	0	-	-	0	-	-	0	-	-	0	-	-
Count Total	7	-	43.75	9	-	56.25	2	-	40.00	3	-	60.00
Number of Lane Exceedances												
0	3	23.10	9.68	1	5.60	3.23	4	30.80	12.90	3	16.70	9.68
1	6	46.20	19.35	11	61.10	35.48	9	69.20	29.03	14	77.80	45.16
2	4	30.80	12.90	5	27.80	16.13	0	-	-	1	5.60	3.23
3	0	-	-	1	5.60	3.23	0	-	-	0	-	-
4	0	-	-	0	-	-	0	-	-	0	-	-
5	0	-	-	0	-	-	0	-	-	0	-	-
6	0	-	-	0	-	-	0	-	-	0	-	-
Count Total	14	-	36.84	24	-	63.16	9	-	36.00	16	-	64.00
Left Curve												
Number of Steering Reversals												
0	5	38.50	16.13	6	33.30	19.35	8	61.50	25.81	13	72.20	41.94
1	7	53.80	22.58	12	66.70	38.71	5	38.50	16.13	1	5.60	3.23
2	1	7.70	3.23	0	-	-	0	-	-	3	16.70	9.68
3	0	-	-	0	-	-	0	-	-	0	-	-
4	0	-	-	0	-	-	0	-	-	1	5.60	3.23
Count Total	9	-	42.86	12	-	57.14	5	-	31.25	11	-	68.75
Number of Lane Exceedances												
0	0	-	-	13	72.20	41.94	6	46.20	19.35	7	38.90	22.58
1	8	61.50	25.81	5	27.80	16.13	7	53.80	22.58	11	61.10	35.48
2	3	23.10	9.68	0	-	-	0	-	-	0	-	-
3	2	15.40	6.45	0	-	-	0	-	-	0	-	-
Count Total	20	-	80.00	5	-	20.00	7	-	38.89	11	-	61.11

Note. %G = proportion of observations relative to the group total for each segment. %T = proportion of observations relative to the sample total for each segment.

[a]Influential outlier case

Outliers

For each curve, *z*-scores were calculated for all continuous dependent variables to identify outlier cases relative to a participant's group mean. In total, this resulted in 1.08% of excluded cases prior to analysis. Of these excluded cases, 18.75% were ASD cases, and 81.25% were TD cases. Further, among the count variables, one ASD outlier emerged in the number of lane exceedances for the right curve. Right curve analyses were run both with and without this case; as the case proved to be influential, the reported results include the analysis where this value was excluded.

Assumptions

Correlations of whole-curve variables can be found in **Table 5.** A square root transformation was applied to all variables whose residuals yielded a significant Shapiro-Wilk test; however, transformed data did not generate different results from untransformed data; therefore, only untransformed data are presented here. Homogeneity of regression slopes was confirmed for all analyses when the covariate was included.

Mean and variance were calculated for count variables in order to determine if data were equidispersed. Steering reversals for the right curve showed equidispersion, while all other variables were slightly underdispersed. However, GEE standard errors are moderately robust to minor violations in this assumption (Giuffrè et al., 2013), so a Poisson distribution was retained. QIC values determined that an independent correlation structure was most appropriate for all count variables. Reported analyses specify if a covariate was included based on lower QICC output value.

Table 5

Correlations for Whole-Curve Variables

Variable	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
						Right Curve													Left Curve											
1. Age	–																													
2. Gender [a,b]	-.18	–																												
3. Months since licensure	.86***	-.16	–																											
4. Days driven per week	.27	-.03	.41*	–																										
5. FSIQ	.15	-.03	.32	.31	–																									
6. Mean longitudinal acceleration	-.01	-.03	.10	.23	.16	–																								
7. Mean longitudinal velocity	-.16	.08	-.30	-.21	-.07	-.81***	–																							
8. Number of lane exceedances [a]	-.23	-.02	-.13	-.13	-.21	-.40*	.18	–																						
9. Percent of time out of line	-.22	.03	-.28	-.12	-.25	-.53**	.47**	.94***	–																					
10. Steering range	-.13	.42*	-.10	.09	.10	-.10	.12	-.11	-.24	–																				
11. SDLP	-.15	-.03	-.27	-.21	-.43*	-.46**	.43*	.41*	.50**	-.20	–																			
12. SD longitudinal acceleration	-.10	.04	-.30	-.19	-.16	-.69***	.66***	.43*	.55**	-.03	.46**	–																		
13. SD longitudinal velocity	-.25	-.27	-.19	-.33	.19	-.26	.29	.18	.24	.20	.04	.27	–																	
14. Steering reversal count [a]	-.32	.37*	-.18	.07	-.05	.02	-.04	-.06	.02	.71**	-.03	.13	.21	–																
15. SD steering angle	-.19	.47**	-.16	.03	.04	-.16	.19	-.07	-.14	.98***	-.09	.04	.23	.77**	–															
16. Mean steering velocity	-.21	.49**	-.20	.01	.06	-.28	.34	-.06	.01	.86***	-.03	.14	.29	.69**	.88***	–														
17. SD steering velocity	-.21	.45*	-.19	-.01	.05	-.31	.33	.03	-.04	.92***	-.06	.09	.31	.72**	.92***	.97***	–													
18. Time to navigate curve	.22	-.10	.36*	.21	.10	.78***	-.98***	-.22	-.48**	-.06	-.44*	-.64***	-.25	.03	-.12	-.25	-.25	–												
19. Mean longitudinal acceleration	-.16	-.14	-.00	.30	-.14	.03	-.17	.28	.26	.13	.05	.02	.14	.22	.15	.11	.11	.16	–											
20. Mean longitudinal velocity	-.11	.07	-.21	-.42*	.12	-.39*	.50**	-.04	-.00	-.02	.23	-.02	.15	-.30	-.02	.01	.11	-.54**	-.42*	–										
21. Number of lane exceedances [a]	-.17	.07	-.06	-.08	.26	.16	-.19	.01	-.09	.05	-.04	-.14	-.26	-.12	.01	.02	-.02	.22	-.55**	-.00	–									
22. Percent of time out of line	-.15	.09	-.14	-.19	.16	.21	-.10	-.00	-.08	-.24	.05	-.25	-.27	-.22	-.21	-.21	-.22	.09	-.57**	.26	.96***	–								
23. Steering range	.07	-.07	.11	.12	.25	-.03	.23	-.01	.08	.07	-.14	.16	.29	.05	.09	.02	-.01	-.19	-.01	-.22	-.05	-.12	–							
24. SDLP	-.29	-.02	-.15	-.06	-.01	-.19	.16	.35	.28	-.18	.34	.05	.03	-.12	-.15	-.10	-.08	-.19	.26	.31	-.05	-.01	-.20	–						
25. SD longitudinal acceleration	-.32	-.06	-.27	-.13	-.00	-.07	.09	.21	.11	-.21	.14	.07	-.00	-.34	-.19	-.15	-.16	-.11	.15	.31	.22	.08	-.17	.72***	–					
26. SD longitudinal velocity	-.01	-.22	-.05	-.21	-.10	-.36*	.24	.04	.15	.04	.41*	.43*	-.03	.13	.08	.13	.08	-.18	-.23	-.04	.22	.14	.02	.15	.23	–				
27. Steering reversal count [a]	-.19	.24	-.28	-.00	.03	-.06	.15	.19	.21	.32	.04	.35	.22	.18	.21	.34	.41*	-.19	.23	-.13	-.26	-.30	.37*	-.10	-.01	.02	–			
28. SD steering angle	.06	-.02	.12	.11	.29	-.05	.25	.01	.06	.08	-.15	.15	.30	-.07	.10	.02	-.00	-.21	-.04	-.16	-.01	-.07	.98***	-.20	-.16	.05	.43*	–		
29. Mean steering velocity	.01	-.09	.05	.15	.22	-.04	.25	.09	.13	.11	-.14	.24	.31	.01	.14	.10	.05	-.21	.02	-.29	-.06	-.13	.97***	-.19	-.17	.09	.57**	.96***	–	
30. SD steering velocity	.07	-.11	.11	.17	.21	-.03	.22	.07	.08	.05	-.16	.19	.28	-.01	.07	-.00	-.03	-.19	.01	-.26	-.04	-.14	.97***	-.16	-.16	-.01	.55**	.96***	.98***	–
31. Time to navigate curve	.11	-.08	.22	.37*	-.08	.37*	-.48**	.06	-.00	.04	-.23	.03	-.06	.28	.06	.03	-.08	.53**	.39*	-.99***	-.03	-.26	.29	-.31	-.30	.10	.15	.24	.36*	.32

Note. FSIQ = full scale IQ; SDLP = standard deviation of lane position; SD = standard deviation

a Denotes use of spearman's rho

b 0 = female and 1 = male

$^{*}p < .05$. $^{**}p < .01$. $^{***}p < .001$.

PCA for Continuous Steering-Related Variables

The six continuous steering-related variables were reduced into principal components using a PCA with no rotation. Component loadings can be found in **Table 6**. Component loadings of all continuous variables can be found in Appendix A.

This analysis yielded 2 principal component scores explaining a total of 85.07% of the variance for the entire set of variables. Component 1 was labeled Steering Wheel Activity due to the high loadings of the following variables: steering range, SD steering angle, mean steering velocity, SD steering velocity. This first component explained 62.95% of the variance. Component 2 was labeled Lateral Vehicle Movement due to the high loadings of the following variables: percent lane exceedances, SDLP. The variance explained by this second factor was 22.13%.

Table 6

Component Loadings for Steering-Related PCA

Variable	1	2
Percent of Time Out of Lane	-.05	**.81**
Steering Range	**.99**	.04
SDLP	-.03	**.82**
SD Steering Angle	**.96**	.05
M Steering Velocity	**.96**	-.03
SD Steering Velocity	**.98**	-.01

Note. Component loadings above .30 are bolded

Primary Data Analyses

Vehicle Dynamic Variables

Table 7 contains the main effects and interaction effects for all vehicle dynamic variables.

Mean Longitudinal Velocity. For the right curve, there was a significant main effect of Segment on mean longitudinal velocity, $F(2.74, 79.36) = 24.68$, $p < .001$, $\eta_p^2 = .46$. **Figure 4** depicts the mean velocity pattern of this curve. The main effect of Group and the Group x Segment interaction were non-significant, both $p > .05$. Inclusion of driving exposure as a covariate did not yield statistically different results; therefore, the reported results exclude the covariates from the model.

For the left curve, there was a significant main effect of Segment on mean longitudinal velocity, $F(1.96, 56.85) = 11.79$, $p < .001$, $\eta_p^2 = .28$. **Figure 4** depicts the mean velocity pattern of this curve. Inclusion of driving exposure as a covariate yielded a between-subjects effect of days driven per week, $F(1, 27) = 4.93$, $p = 0.04$, $\eta_p^2 = .15$. Therefore, days driven per week was included in the model to interpret between-subjects effects. However, the main effect of Group and the Group x Segment interaction were non-significant, both $p > .05$.

SD Longitudinal Velocity. For the right curve, there was a significant main effect of Segment on SD longitudinal velocity, $F(2.49, 67.27) = 5.87$, $p = .002$, $\eta_p^2 = .18$. **Figure 5** depicts the SD velocity pattern of this curve. The main effect of Group and the Group x Segment interaction were non-significant, both $p > .05$. Inclusion of driving exposure as a covariate did not yield statistically different results; therefore, the reported results exclude the covariates from the model.

Table 7

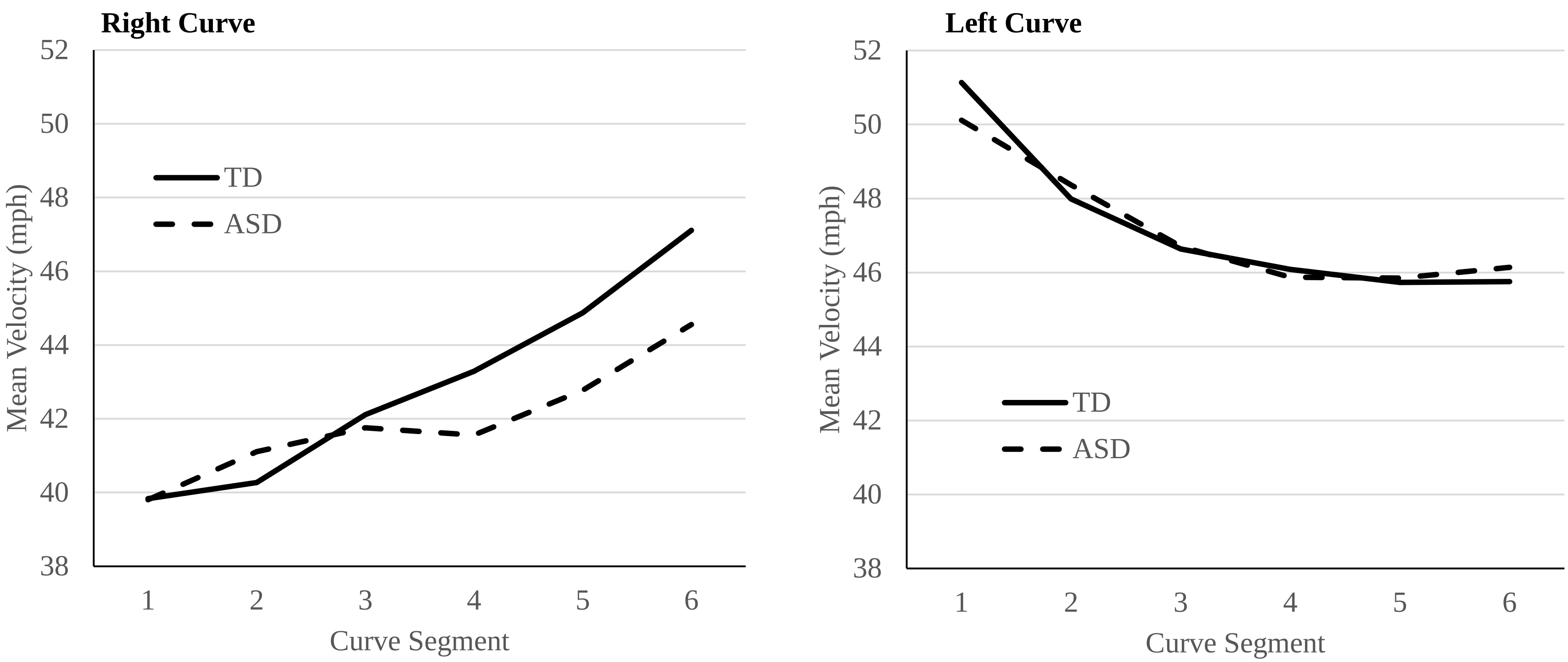
Repeated Measures ANOVA Main Effects and Interactions

Variable	Factor	Right Curve *F*	Right Curve *p*	Right Curve η_p^2	Left Curve *F*	Left Curve *p*	Left Curve η_p^2
Vehicle Dynamic Variables							
M Longitudinal Velocity	Group	$F(1, 29) = .30$	.59	.01	$F(1, 27) = .30$[a]	.59	.15
	Segment	$F(2.74, 79.36) = 24.68$	< .001***	.46	$F(1.96, 56.85) = 11.79$	< .001***	.28
	Group x Segment	$F(2.74, 79.36) = 2.32$	.09	.07	$F(2.24, 60.38) = .35$[a]	.73	.01
SD Longitudinal Velocity	Group	$F(1, 27) = .22$	.64	.01	$F(1, 27) = .05$	.82	.002
	Segment	$F(2.49, 67.27) = 5.87$	< .01**	.18	$F(3.03, 81.86) = 4.71$	<.01**	.15
	Group x Segment	$F(2.49, 67.27) = .18$	.88	.01	$F(3.03, 81.86) = 1.49$	.22	.05
M Longitudinal Acceleration	Group	$F(1, 29) = .42$	.52	.01	$F(1, 28) = 1.34$	.26	.05
	Segment	$F(2.88, 83.44) = 48.17$	< .001***	.62	$F(3.77, 105.47) = 96.95$	< .001***	.78
	Group x Segment	$F(2.88, 83.44) = .26$	.85	.01	$F(3.77, 105.47) = .40$	.80	.01
SD Longitudinal Acceleration	Group	$F(1, 25) = 1.66$	.21	.06	$F(1, 26) = .45$[a]	.51	.02
	Segment	$F(2.54, 68.57) = 17.4$	< .001***	.39	$F(3.83, 107.12) = 24.06$	< .001***	.22
	Group x Segment	$F(2.76, 69.02) = .88$[b]	.45	.04	$F(4.29, 111.64) = .50$[a]	.75	.02
Steering-Related Variables (Composite)							
Steering Wheel Activity	Group	$F(1, 24) = 2.28$	.14	.09	$F(1, 22) = .13$	.72	.01
	Segment	$F(3.96, 94.92) = 3.70$	.01*	.13	$F(1.27, 28.03) = 5.67$	.02*	.21
	Group x Segment	$F(3.96, 94.92) = 0.66$	.62	.03	$F(1.27, 28.03) = .20$	.72	.01
Lateral Vehicle Movement	Group	$F(1, 23) = 0.00$[b]	.95	.00	$F(1, 22) = .20$	.66	.01
	Segment	$F(4.22, 101.25) = 10.95$	< .001***	.31	$F(5, 110) = 13.25$	<.001***	.38
	Group x Segment	$F(4.38, 101.81) = 1.17$[b]	.33	.05	$F(5, 110) = .76$	.58	.03

a Days driven per week included as covariate in model
b Months since licensure included as covariate in model
**p* < .05. ***p* < .01. ****p* < .001.

Figure 4

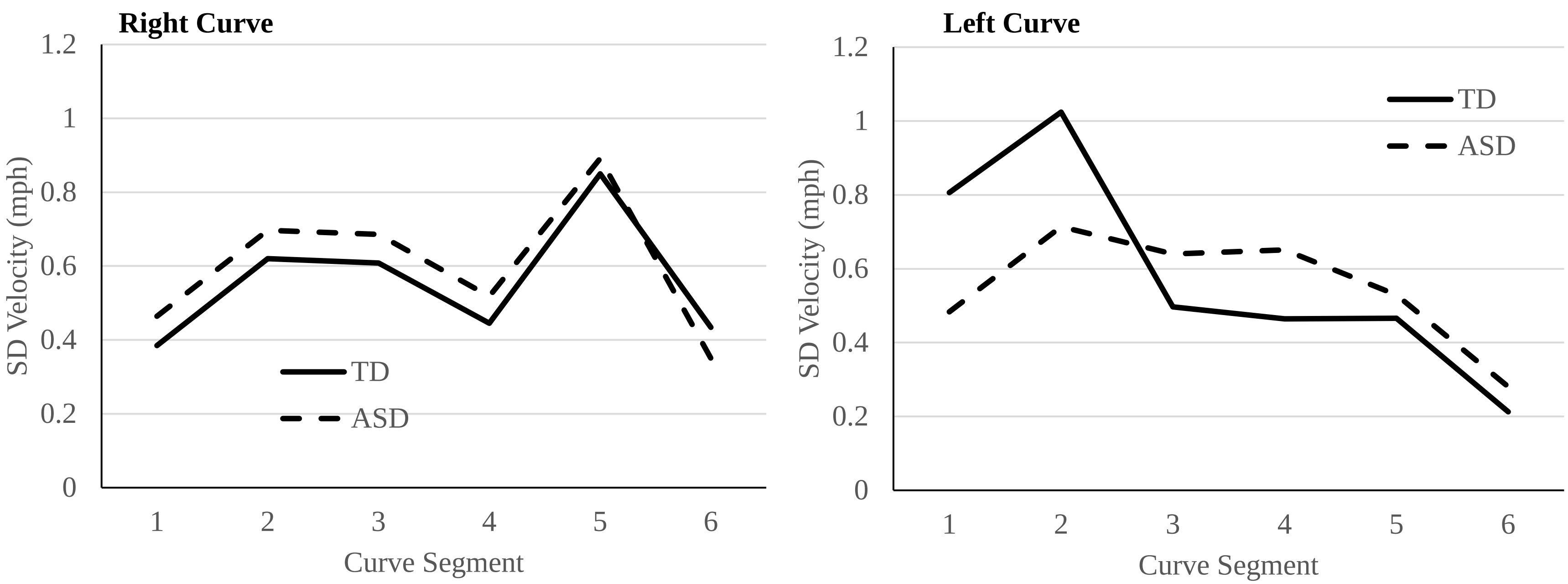
Mean Longitudinal Velocity by Group Across Curve Segments



Note. 1 = approach tangent, 2 = curve entry, 3 = apex entry, 4 = apex exit, 5 = curve exit, 6 = exit tangent.

Figure 5

Standard Deviation of Longitudinal Velocity by Group Across Curve Segments



Note. 1 = approach tangent, 2 = curve entry, 3 = apex entry, 4 = apex exit, 5 = curve exit, 6 = exit tangent.

For the left curve, there was a significant main effect of Segment on SD longitudinal velocity, $F(3.03, 81.86) = 4.71$, $p = .004$, $\eta_p^2 = .15$. **Figure 5** depicts the SD longitudinal velocity pattern of this curve. The main effect of Group and the Group x Segment interaction were non-significant, both $p > .05$. Inclusion of driving exposure as a covariate did not yield statistically different results; therefore, the reported results exclude the covariates from the model.

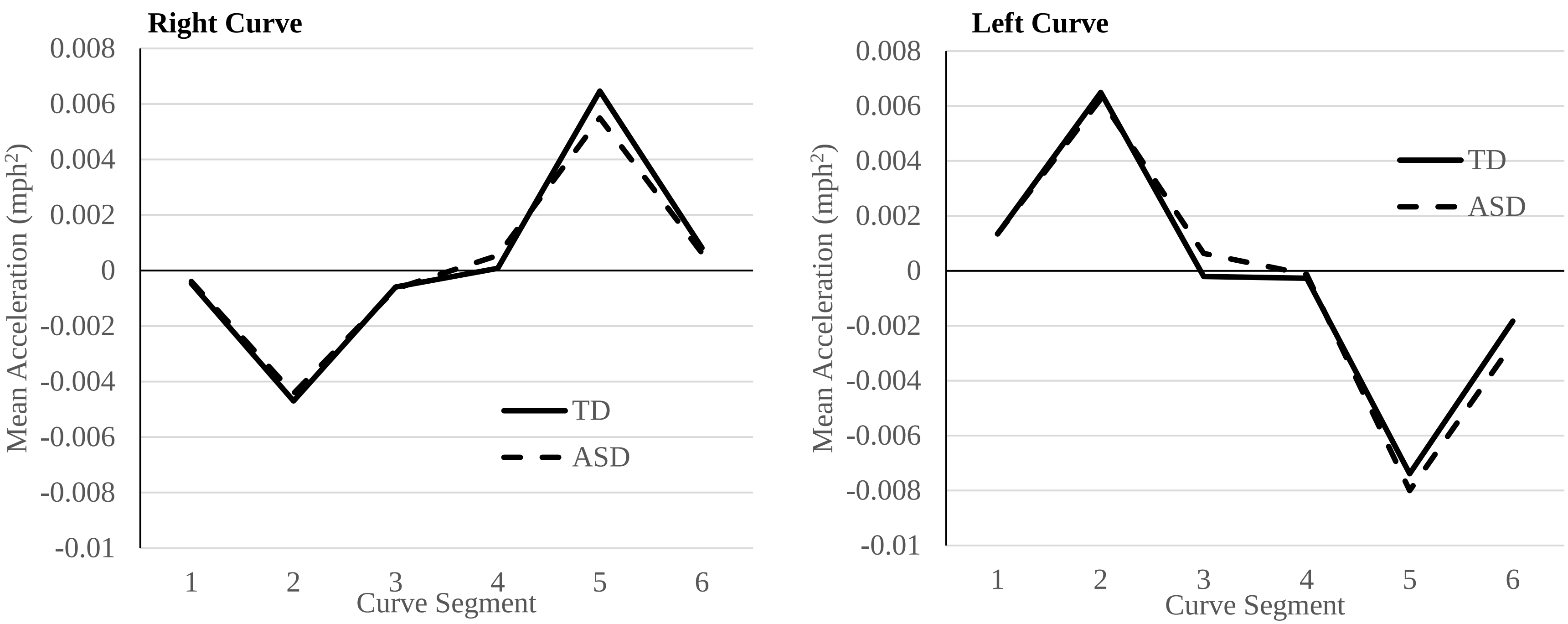
Mean Longitudinal Acceleration. For the right curve, there was a significant main effect of Segment on mean longitudinal acceleration, $F(2.88, 83.44) = 48.17$, $p < .001$, $\eta_p^2 = .62$. **Figure 6** depicts the mean acceleration pattern of this curve. The main effect of Group and the Group x Segment interaction were non-significant, both $p > .05$. Inclusion of driving exposure as a covariate did not yield statistically different results; therefore, the reported results exclude the covariates from the model.

For the left curve, there was a significant main effect of Segment on mean longitudinal acceleration, $F(3.77, 105.47) = 96.95$, $p < .001$, $\eta_p^2 = .78$. **Figure 6** depicts the mean acceleration pattern of this curve. The main effect of Group and the Group x Segment interaction were non-significant, both $p > .05$. Inclusion of driving exposure as a covariate did not yield statistically different results; therefore, the reported results exclude the covariates from the model.

SD Longitudinal Acceleration. For the right curve, there was a significant main effect of Segment on SD longitudinal acceleration, $F(2.54, 68.57) = 17.4$, $p < .001$, $\eta_p^2 = .39$. **Figure 7** depicts the SD acceleration pattern of this curve. Inclusion of driving exposure as a covariate yielded a between-subjects effect of months since licensure, $F(1, 25) = 4.907$, $p = .04$, $\eta_p^2 = .16$. Therefore, months since licensure was included in the

Figure 6

Mean Longitudinal Acceleration by Group Across Curve Segments



Note. 1 = approach tangent, 2 = curve entry, 3 = apex entry, 4 = apex exit, 5 = curve exit, 6 = exit tangent.

model to interpret between-subjects effects. However, the main effect of Group and the Group x Segment interaction were non-significant, both $p > .05$.

For the left curve, there was a significant main effect of Segment on SD longitudinal acceleration, $F(3.83, 107.12) = 24.06$, $p < .001$, $\eta_p^2 = .46$. **Figure 7** depicts the SD acceleration pattern of this curve. Inclusion of driving exposure as a covariate yielded a between-subjects effect of days driven per week, $F(1, 26) = 7.51$, $p = 0.01$, $\eta_p^2 = .22$. Therefore, days driven per week was included in the model to interpret between-subjects effects. However, the main effect of Group and the Group x Segment interaction were non-significant, both $p > .05$.

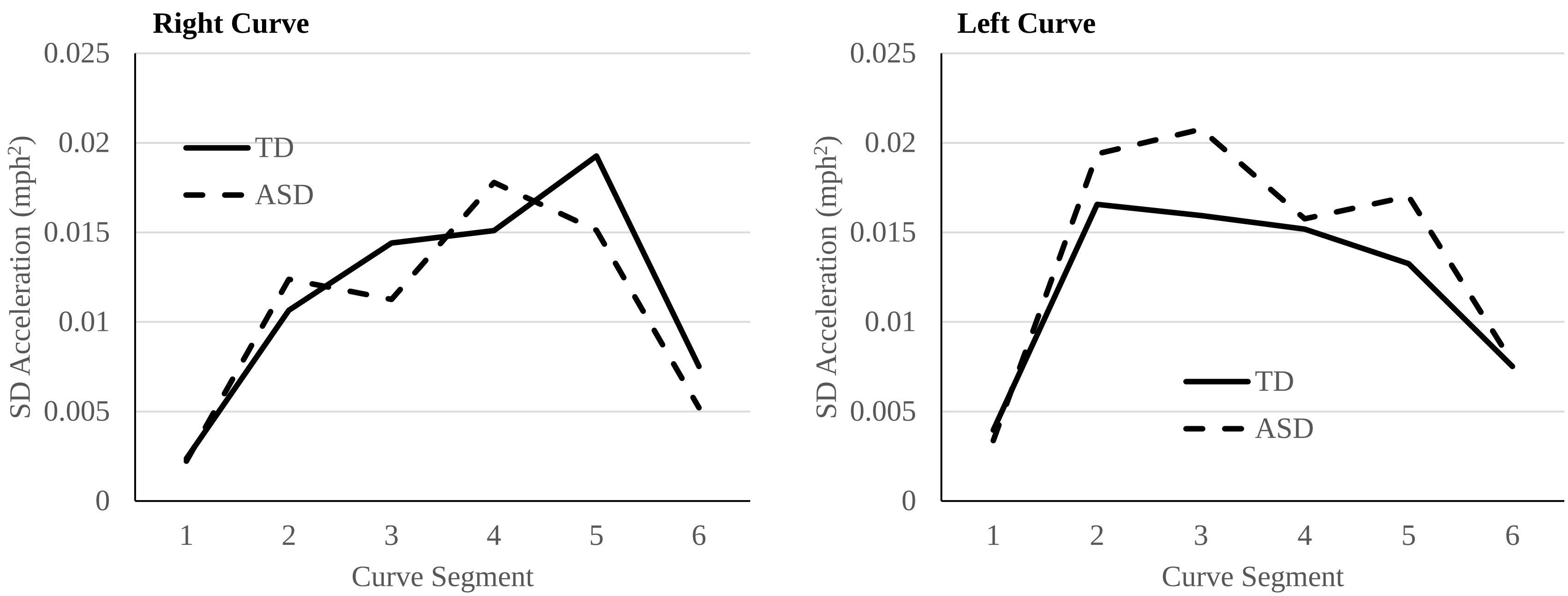
Steering-Related Variables

Table 7 contains the main effects and interaction effects for RM-ANOVAs conducted on composite steering-related variables. **Tables 8** and **9** contain GEE results for the number of steering reversals and lane exceedances, respectively. See Appendix B for main and interaction effects of raw continuous steering-related variables, and Appendix C for steering performance patterns for each raw steering-related variable.

Steering Wheel Activity. For the right curve, there was a significant main effect of Segment on steering wheel activity, $F(3.96, 94.92) = 3.70$, $p = .01$, $\eta_p^2 = .13$. **Figure 8** depicts the steering wheel activity pattern of this curve. The main effect of Group and the Group x Segment interaction were non-significant, both $p > .05$. Inclusion of driving exposure as a covariate did not yield statistically different results; therefore, the reported results exclude the covariates from the model.

Figure 7

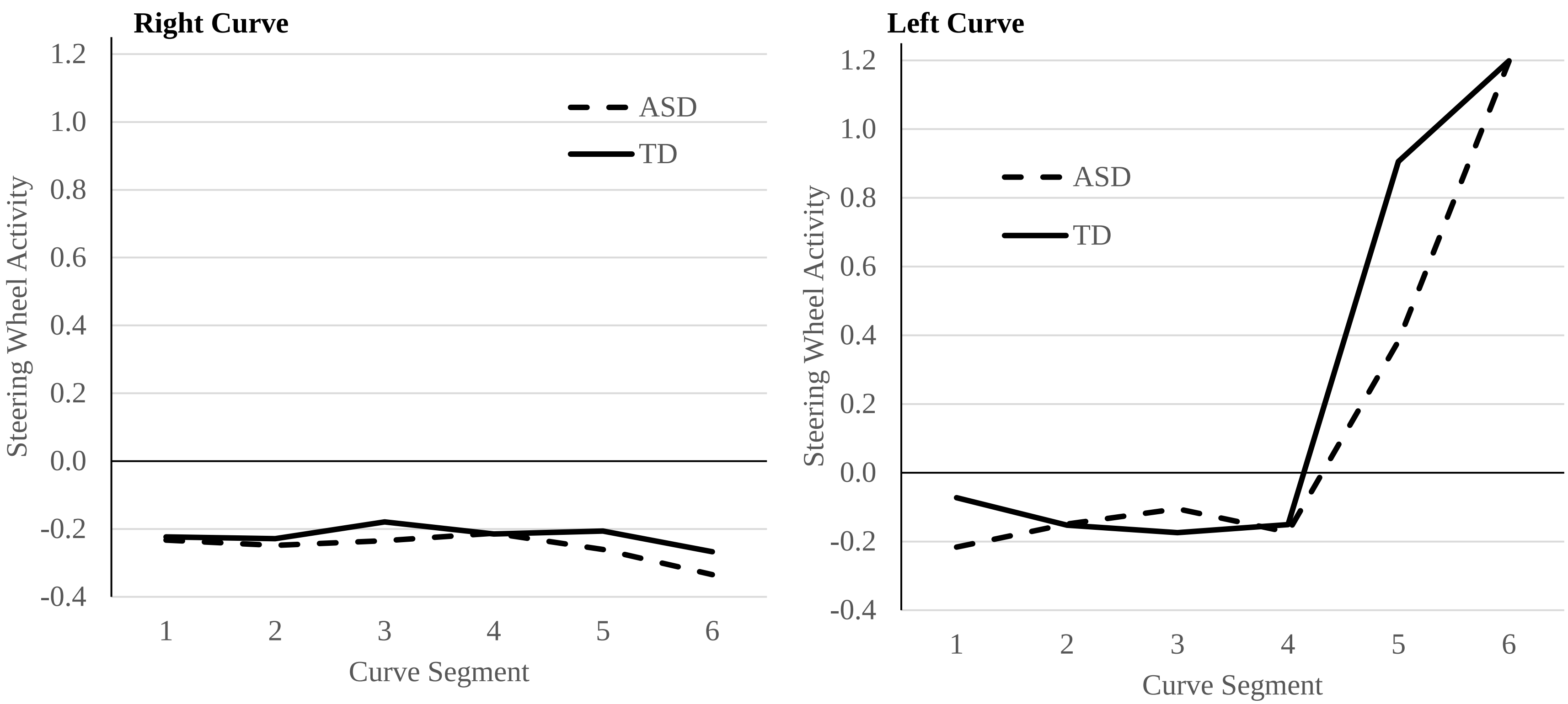
Standard Deviation of Longitudinal Acceleration by Group Across Curve Segments



Note. 1 = approach tangent, 2 = curve entry, 3 = apex entry, 4 = apex exit, 5 = curve exit, 6 = exit tangent.

Figure 8

Steering Wheel Activity by Group Across Curve Segments



Note. 1 = approach tangent, 2 = curve entry, 3 = apex entry, 4 = apex exit, 5 = curve exit, 6 = exit tangent

For the left curve, there was a significant main effect of Segment on steering wheel activity, $F(1.27, 28.03) = 5.67$, $p = .02$, $\eta_p^2 = .21$. **Figure 8** depicts the steering wheel activity pattern of this curve. The main effect of Group and the Group x Segment interaction were non-significant, both $p > .05$. Inclusion of driving exposure as a covariate did not yield statistically different results; therefore, the reported results exclude the covariates from the model.

Lateral Vehicle Movement. For the right curve, there was a significant main effect of Segment on lateral vehicle movement, $F(4.22, 101.25) = 10.95$, $p < .001$, $\eta_p^2 = .31$. **Figure 9** depicts the lateral vehicle movement pattern of this curve. Inclusion of driving exposure as a covariate yielded a between-subjects effect of months since licensure, $F(1, 23) = 5.29$, $p = .03$, $\eta_p^2 = .19$. Therefore, months since licensure was included in the model to interpret between-subjects effects. However, the main effect of Group and the Group x Segment interaction were non-significant, both $p > .05$.

For the left curve, there was a significant main effect of Segment on lateral vehicle movement, $F(5, 110) = 13.25$, $p < .001$, $\eta_p^2 = .38$. **Figure 9** depicts the lateral vehicle movement pattern of this curve. The main effect of Group and the Group x Segment interaction were non-significant, both $p > .05$. Inclusion of driving exposure as a covariate did not yield statistically different results; therefore, the reported results exclude the covariates from the model.

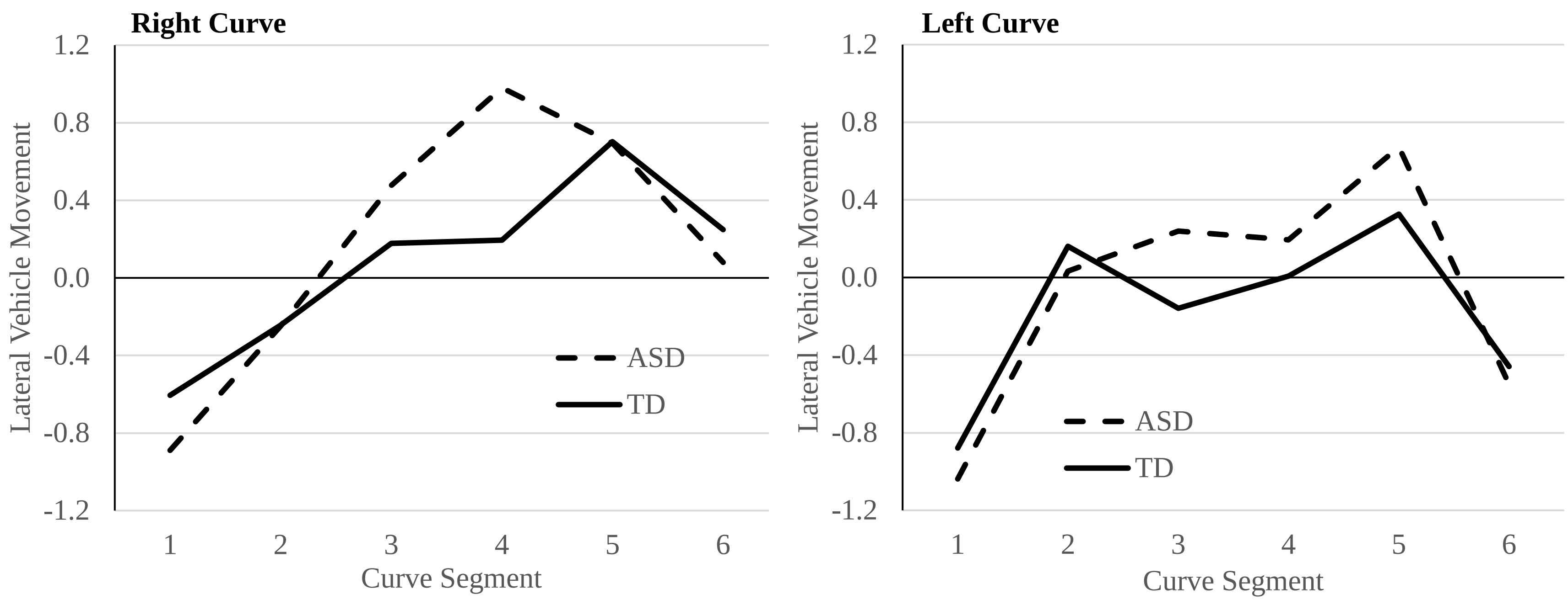
Number of Steering Reversals. For the right curve, inclusion of covariates did not improve model fit and were therefore excluded from analysis. Overall across both groups, Curve Segment significantly predicted steering reversal rate ($\chi^2 = 22.67$, $p < .001$). However, significant differences in rate ratios were not reflected in the chosen reference group. Pairwise comparisons between all segments indicated that, when compared to the exit tangent, the rates of steering reversals significantly increased by 233% at curve entry (χ^2 = 6.40, RR = 3.33, CI = 1.31-8.48), 400% at apex entry (χ^2 = 8.57, RR = 5.00, CI = 1.70-14.87), and 267% at apex exit (χ^2 = 5.47, RR = 3.67, CI = 1.23-10.89). The overall Group effect (p = .67) as well as all Group x Segment interaction parameter estimates (all p > .05) were non-significant. **Figure 10** shows the RR values for each group when compared to the exit tangent.

Dummy-coded contrasts for the right curve revealed that, compared to the first half of the curve, the rate of steering reversals during the second half of the curve decreased by 32% (χ^2 = 4.84, RR = .68, CI = .48-.96) for all participants. Compared to the rest of the curve, the rate of steering reversals during apex entry and apex exit increased by 68% for all participants (χ^2 = 5.13, RR = 1.68, CI = 1.07-2.63).

For the left curve, inclusion of covariates did not improve model fit and were therefore excluded from analysis. Curve Segment significantly predicted steering reversal rate such that, for both groups, compared to the approach tangent segment, the rate of steering reversals significantly increased at curve entry by 50% (χ^2 = 4.26, RR = 1.5, CI = 1.02-2.20). Further, the Group x Curve Segment interaction significantly predicted the rate of steering reversals. Compared to the TD group at the approach tangent, the ASD group was 4.33 times more likely to engage in steering reversals during curve entry (χ^2 = 6.05, RR = 4.33, CI = 1.35-13.93), 9.23 times more likely at apex entry (χ^2 = 9.37, RR = 9.23, CI = 2.23-38.30), 4.36 times more likely at apex exit (χ^2 = 4.49, RR = 4.36, CI = 1.12-17.06), and 4.5 times more likely curve exit (χ^2 = 4.31, RR = 4.50, CI = 1.09-18.61). **Figure 11** shows the RR values for each group when compared to the approach tangent.

Figure 9

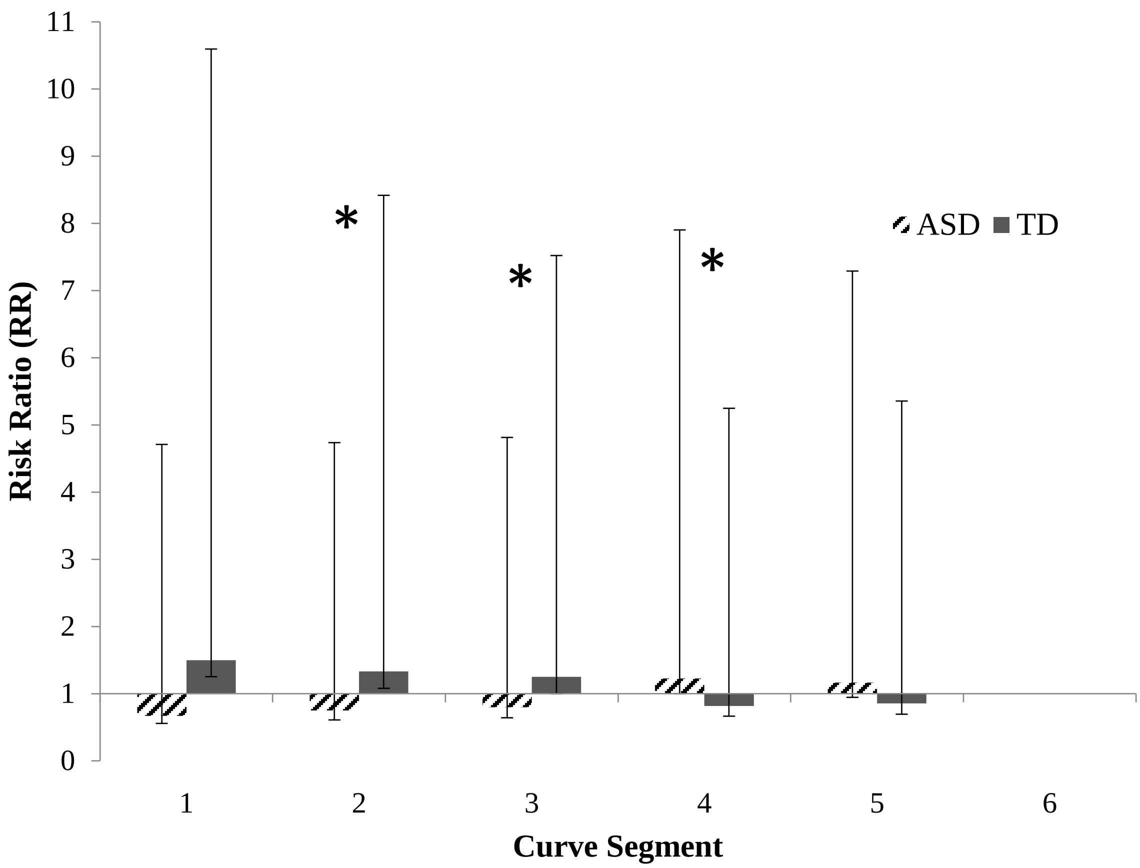
Lateral Vehicle Movement by Group Across Curve Segments



Note. 1 = approach tangent, 2 = curve entry, 3 = apex entry, 4 = apex exit, 5 = curve exit, 6 = exit tangent.

Figure 10

Risk Ratio Values for Steering Wheel Reversals at Right Curve



Note. The reference group is set at the exit tangent. Curve Segment significantly predicted steering reversal rate ($\chi^2 = 22.67$, $p < .001$). Segments that differed significantly from the exit tangent are marked with an asterisk. 1 = approach tangent, 2 = curve entry, 3 = apex entry, 4 = apex exit, 5 = curve exit, 6 = exit tangent.

Dummy-coded contrasts for the left curve revealed that, compared to the rest of the curve, the ASD group was 2.13 times more likely to engage in steering reversals during apex entry and apex exit (χ^2 = 6.40, RR = 2.13, CI = 1.19-3.84).

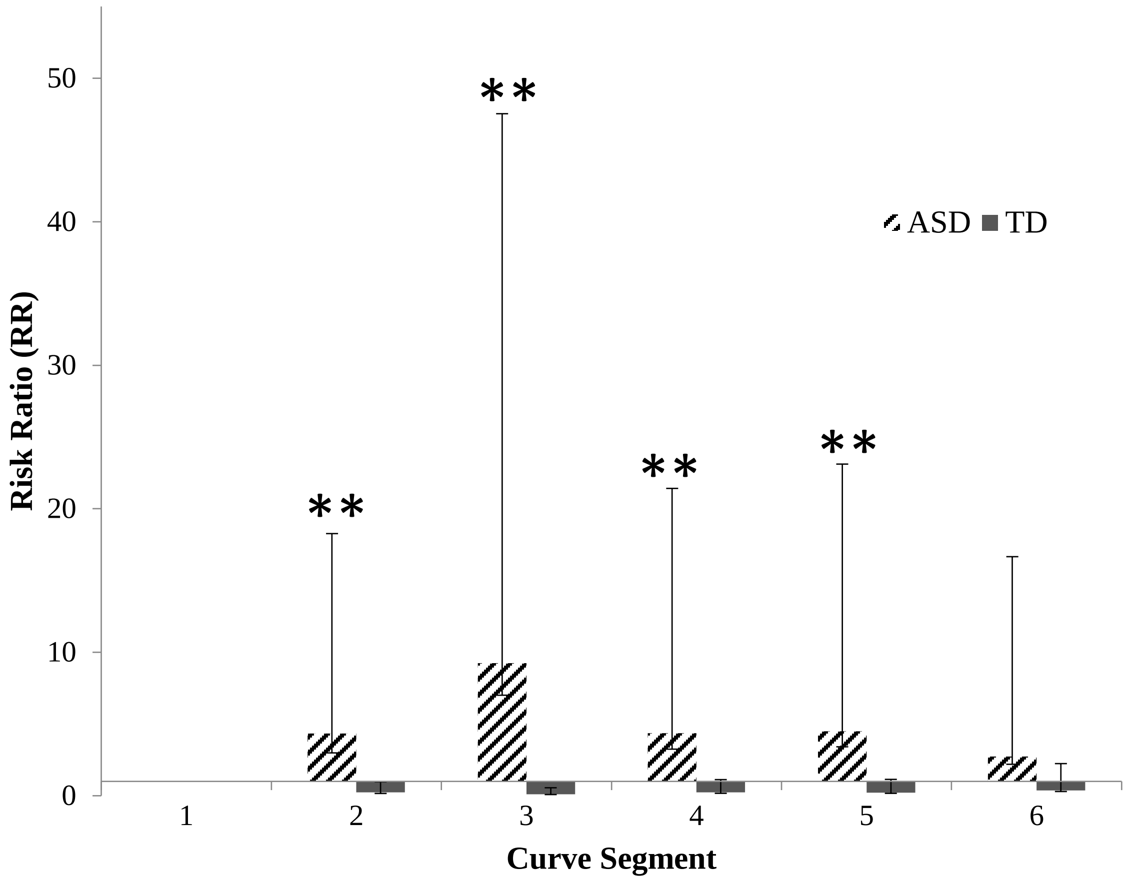
Number of Lane Exceedances. For the right curve, inclusion of the months since licensure covariate significantly improved the QICC value and was therefore included in all analyses. For every additional month of licensure, the rate of lane exceedances decreased by 1% (χ^2 = 4.05, RR =.99, CI = .98-.99). Curve Segment significantly predicted the number of lane exceedances such that, compared to the approach tangent segment, the rate of lane exceedances significantly increased for all participants at the apex entry by 100% (χ^2 = 18.04, RR = 2.00, CI = 1.45-2.75), apex exit by 54% (χ^2 = 5.48, RR = 1.54, CI = 1.07-2.21), and curve exit by 85% (χ^2 = 15.30, RR = 1.85, CI = 1.36-2.51). **Figure 12** shows the RR values for each group when compared to the approach tangent. The overall Group effect (*p* = .17) as well as all Group x Segment interaction parameter estimates (all *p* > .05) were not significant predictors of lane exceedance rate.

Dummy-coded contrasts for the right curve revealed that, compared to the rest of the curve, the rate of lane exceedances during apex entry and apex exit increased by 31% for all participants (χ^2 = 9.82, RR = 1.31, CI = 1.11 - 1.56).

For the left curve, inclusion of covariates did not improve model fit and were therefore excluded from analysis. Curve Segment significantly predicted the rate of lane exceedances such that, compared to the approach tangent segment, the rate of lane exceedances significantly increased for all participants at the curve entry by 150% (χ^2 = 11.99, RR = 2.50, CI = 1.49-24.20), apex entry by 163% (χ^2 = 6.69, RR = 2.63, CI = 1.26-5.45), apex exit by 250% (χ^2 = 17.58, RR =3.5, CI = 1.95-6.29), and curve exit by

Figure 11

Risk Ratio Values for Steering Wheel Reversals at Left Curve



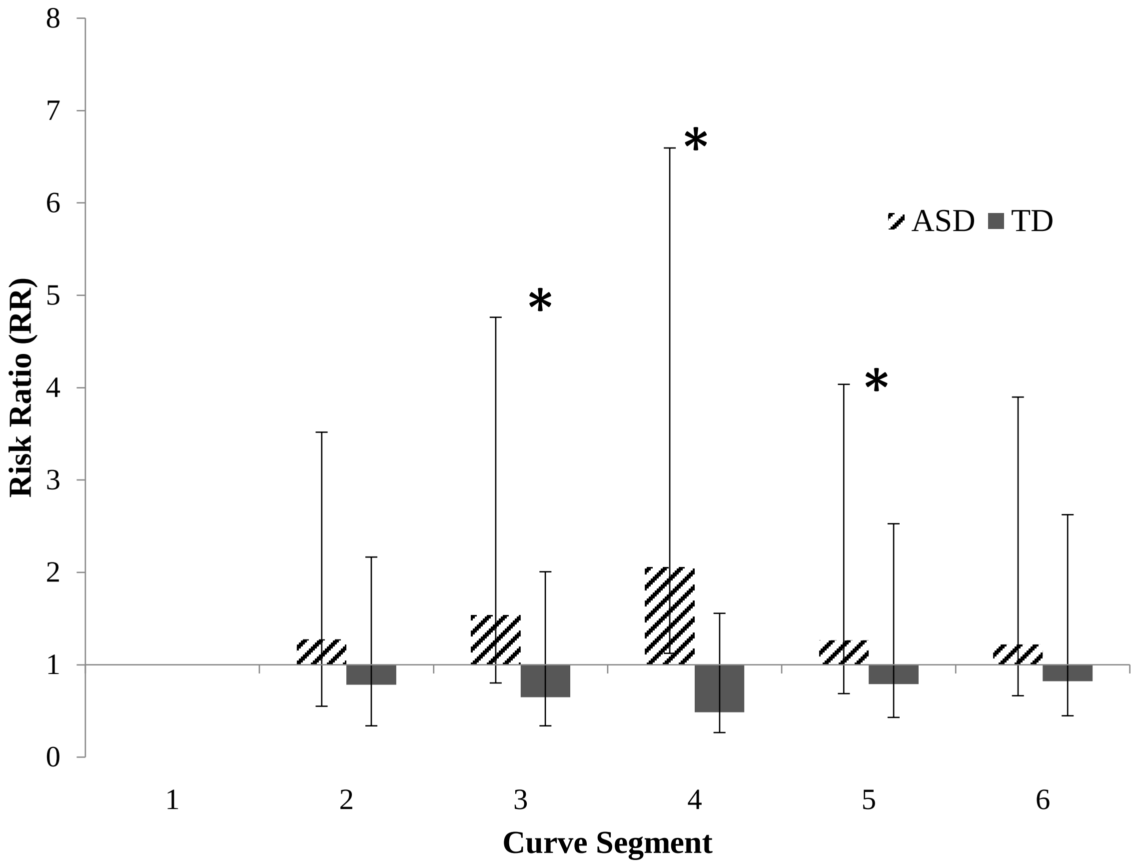
Note. The reference group is set at the approach tangent. The Group x Curve Segment interaction significantly predicted steering reversal rate ($\chi^2 = 13.25$, $p = .02$). Groups that differed significantly from each other when compared to the approach tangent are marked with two asterisks.1 = approach tangent, 2 = curve entry, 3 = apex entry, 4 = apex exit, 5 = curve exit, 6 = exit tangent.

188% (χ^2 = 16.45, RR = 2.88, CI = 1.73-4.79). The Group x Segment interaction significantly predicted the rate of lane exceedances (χ^2 = 15.41, p = .01). However, significant differences in rate ratios were not reflected in the chosen reference group. Pairwise comparisons between all segments indicated that, compared to the TD group at curve entry, the rates of lane exceedances for the ASD group significantly increased by 58% at curve exit (χ^2 = 4.39, RR = 1.58, CI = 1.03-2.43). **Figure 13** shows the RR values for each group when compared to the exit tangent. Group alone was not a significant predictor of lane exceedance rate (p = .52).

Dummy-coded contrasts for the left curve revealed that, compared to the first half of the curve, the rate of lane exceedances significantly increased by 27% for all participants during the second half of the curve (χ^2 = 4.44, RR = 1.27, CI = 1.02-1.58). Compared to the rest of the curve, the rate of lane exceedances significantly increased by 58% for all participants during apex entry and apex exit (χ^2 = 7.37, RR = 1.58, CI = 1.14-2.20).

Figure 12

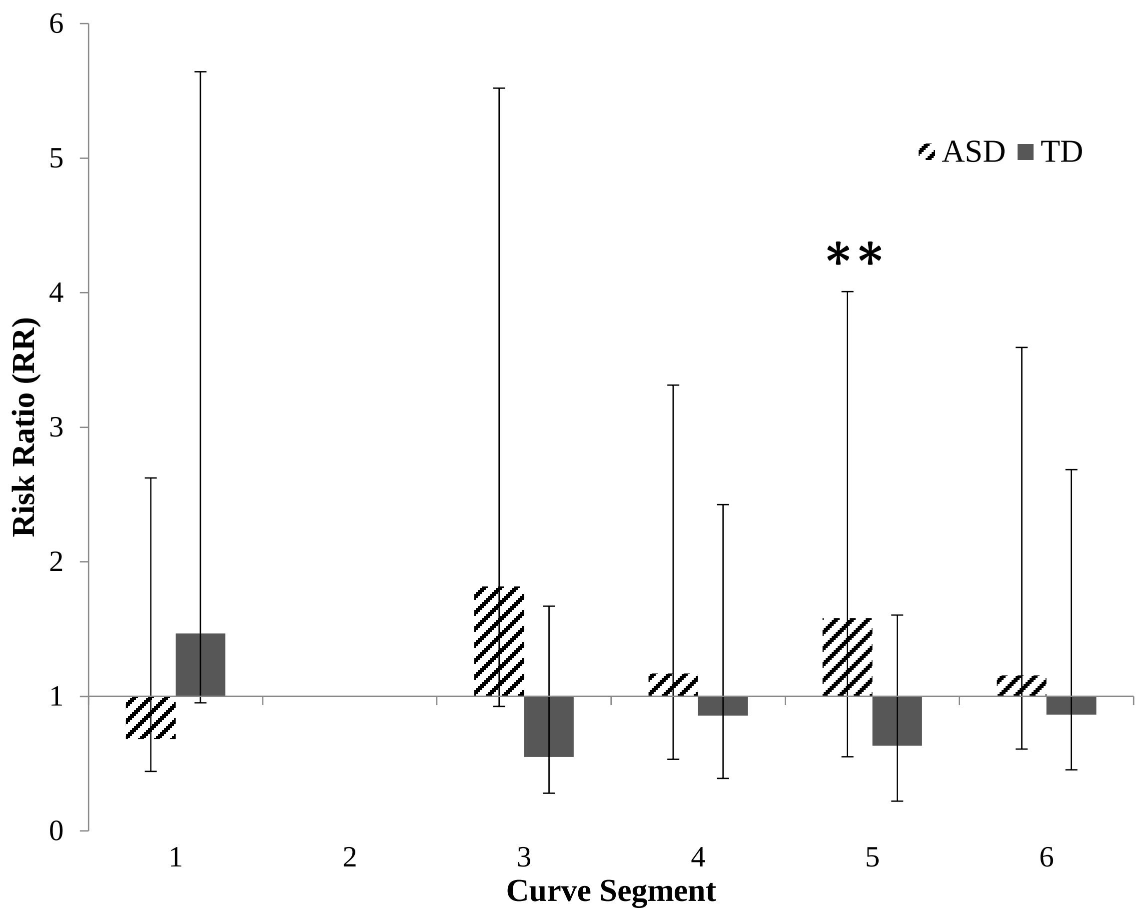
Risk Ratio Values for Lane Exceedances at Right Curve



Note. The reference group is set at the approach tangent. Months since licensure is included in the model as a covariate. Curve Segment significantly predicted lane exceedance rate (χ^2 = 31.72, p < .001). Segments that differed significantly from the approach tangent are marked with an asterisk. 1 = approach tangent, 2 = curve entry, 3 = apex entry, 4 = apex exit, 5 = curve exit, 6 = exit tangent.

Figure 13

Risk Ratio Values for Lane Exceedances at Left Curve



Note. The reference group is set at curve entry. The Group x Curve Segment interaction significantly predicted lane exceedance rate (χ^2 = 15.41, p = .01). Groups that differed significantly from each other when compared to curve entry are marked with two asterisks. 1 = approach tangent, 2 = curve entry, 3 = apex entry, 4 = apex exit, 5 = curve exit, 6 = exit tangent.

Table 8

Association Between Group, Segment, and Rate of Steering Reversals

Variable	Right Curve					Left Curve				
	Wald χ^2	RR	CI LL	CI UL	*p*	Wald χ^2	RR	CI LL	CI UL	*p*
Group										
ASD	0.85	0.62	0.22	1.73	.36	4.13	0.23	0.06	0.95	.04*
TD	-	-	-	-	-	-	-	-	-	-
Curve Segment										
Approach Tangent	-	-	-	-	-	-	-	-	-	-
Curve Entry	0.06	1.11	0.48	2.59	.81	4.26	1.50	1.02	2.20	.04*
Apex Entry	2.28	1.67	0.86	3.24	.13	0.05	1.08	0.52	2.24	.83
Apex Exit	0.35	1.22	0.63	2.38	.56	0.07	0.92	0.48	1.75	.79
Curve Exit	0.00	1.00	0.59	1.71	1.00	0.00	1.00	0.52	1.92	1.00
Exit Tangent	3.49	0.33	0.11	1.06	.06	0.02	0.92	0.27	3.13	.89
Group x Curve Segment										
ASD x Approach Tangent	-	-	-	-	-	-	-	-	-	-
ASD x Curve Entry	0.06	1.13	0.43	2.92	.81	6.05	4.33	1.35	13.93	.01*
ASD x Apex Entry	0.14	1.20	0.46	3.13	.71	9.37	9.23	2.23	38.30	< .01**
ASD x Apex Exit	1.50	1.84	0.69	4.89	.22	4.49	4.36	1.12	17.01	.03*
ASD x Curve Exit	1.19	1.75	0.64	4.78	.28	4.31	4.50	1.09	18.61	.04*
ASD x Exit Tangent	0.19	1.50	0.25	9.10	.66	1.45	2.73	0.53	13.99	.23
Second Half vs. First Half of Curve										
First Half	-	-	-		-	-	-	-	-	-
Second Half	4.84	0.68	0.48	0.96	.03*	0.72	0.79	0.46	1.36	.40
ASD	0.84	0.69	0.32	1.52	.36	0.28	1.13	0.72	1.76	.60
ASD x Second Half	1.95	1.57	0.83	2.94	.16	0.48	0.80	0.42	1.52	.49
Curve Apexes vs. All Other Segments										
Curve Apexes	5.13	1.68	1.07	2.63	.03*	0.16	0.91	0.56	1.48	.69
All Other Segments	-	-	-	-	-	-	-	-	-	-
ASD	0.34	0.80	0.39	1.68	.56	1.36	0.76	0.48	1.21	.24
ASD x Curve Apexes	0.11	1.13	0.55	2.31	.75	6.39	2.13	1.19	3.84	.01*

Note. A dash denotes the reference group. R = rate ratio, CI LL = 95% confidence interval lower limit, CI UL = 95% confidence interval upper limit. *p < .05. **p < .01. ***p < .001.

Table 9

Association Between Group, Segment, and Rate of Lane Exceedances

Variable	Right Curve					Left Curve				
	Wald χ^2	RR	CI LL	CI UL	*p*	Wald χ^2	RR	CI LL	CI UL	*p*
Group										
ASD	2.24	0.61	0.32	1.16	.13	1.32	0.52	0.17	1.59	.25
TD	-	-	-		-	-	-	-		-
Curve Segment										
Approach Tangent	-	-	-		-		-	-		-
Curve Entry	2.41	1.31	0.93	1.83	.12	11.99	2.50	1.49	4.20	< .001 **
Apex Entry	18.04	2.00	1.45	2.75	< .001***	6.69	2.63	1.26	5.45	.01*
Apex Exit	5.48	1.54	1.07	2.21	.02*	17.58	3.50	1.95	6.29	< .001***
Curve Exit	15.30	1.85	1.36	2.51	< .001***	16.45	2.88	1.73	4.79	< .001***
Exit Tangent	1.35	1.23	0.87	1.75	.25	1.28	1.38	0.79	2.39	.26
Group x Curve Segment										
ASD x Approach Tangent	-	-	-		-	-	-	-		-
ASD x Curve Entry	0.71	1.28	0.72	2.24	.40	0.52	1.47	0.52	4.18	.47
ASD x Apex Entry	1.38	1.55	0.75	3.24	.24	2.57	2.67	0.80	8.86	.11
ASD x Apex Exit	3.20	2.06	0.93	4.54	.07	0.79	1.71	0.52	5.62	.37
ASD x Curve Exit	0.34	1.26	0.58	2.77	.56	2.39	2.32	0.80	6.74	.12
ASD x Exit Tangent	0.24	1.22	0.55	2.68	.62	1.04	1.70	0.61	4.70	.31
Second Half vs. First Half of Curve										
First Half	-	-	-		-					
Second Half	0.27	1.07	0.83	1.39	.61	4.44	1.27	1.02	1.52	.04*
ASD	1.03	0.84	0.59	1.18	.31	0.01	0.99	0.73	1.35	.94
ASD x Second Half	0.44	1.16	0.76	1.78	.50	0.01	1.02	0.74	1.40	.92
Curve Apexes vs. All Other Segments										
Curve Apexes	9.82	1.31	1.11	1.56	< .01**	7.37	1.58	1.14	2.20	< .01**
All Other Segments	-	-	-	-	-	-	-	-		-
ASD	3.43	0.74	0.54	1.02	.06	0.24	0.92	0.65	1.30	.62
ASD x Curve Apexes	3.19	1.46	0.96	2.22	.07	0.62	1.20	0.76	1.91	.43

Note. A dash denotes the reference group for analysis. Right curve results adjusted for months since licensure. RR = rate ratio, CI LL = 95% confidence interval lower limit, CI UL = 95% confidence interval upper limit

**p* < .05. ***p* < .01. ****p* < .001.

DISCUSSION

The present study was conducted to compare the curve negotiation profiles of drivers with and without ASD in a simulated driving environment. Because driving profiles and negotiation strategies differed significantly between the right and left curves, their findings are discussed separately.

Vehicle Dynamic Hypotheses

When negotiating the right curve, the vehicle dynamic profiles of drivers with ASD in this sample were nearly identical to those of TD drivers and aligned with patterns typically seen in the TD curve negotiation literature (Campbell et al., 2012; McKnight & Adams, 1970). Participants entered the approach tangent at approximately the same speed, decelerated from approach tangent to curve entry, maintained a relatively constant speed through apex entry and exit (thereby maintaining a near-zero longitudinal acceleration), and finally accelerated at curve exit to achieve a constant velocity at the exit tangent. The pattern of velocity variability within each curve segment, as measured by SD velocity, was also nearly identical across groups. Participant velocity fluctuated the most at curve exit, which would be expected given the acceleration profile at this curve segment.

The vehicle dynamic profiles of drivers with ASD were also nearly identical to those of TD drivers during the left curve; however, these profiles differed substantially from those of the right curve. Participants had a reduced speed at approach tangent during the right curve (M_{TOTAL} = 39.82 mph) and steadily increased their velocity during curve negotiation. Alternately, participants entered the left curve at a higher velocity (M_{TOTAL} =

50.63 mph) and had a near constant reduction in velocity until apex entry, at which participants maintained a relatively constant velocity for the remainder of the curve (M_{TOTAL} = 45.95 mph). This also resulted in a longitudinal acceleration profile that differed from the right curve and, by extension, the expected pattern during safe curve negotiation. Participants accelerated during curve entry, maintained a constant velocity through apex entry and exit (thereby maintaining a near-zero longitudinal acceleration), and then decelerated during curve exit to reach a constant, reduced speed at the exit tangent. This altered profile may be due to the higher speed at approach tangent; in realizing they entered the curve at a velocity exceeding their threshold for comfortable and safe curve negotiation, participants may have coasted around the curve apexes and subsequently decelerated at the end of the curve to attain a velocity comparable to that of the right curve upon curve exit.

Findings did not support vehicle dynamic hypotheses positing that, across the whole curve, drivers with ASD would drive more slowly, have a higher acceleration, and have a higher SD velocity and acceleration relative to TD drivers. They also did not support hypotheses that drivers with ASD would have a lower velocity at the beginning and end of curves, a lower longitudinal acceleration during apex navigation, and a higher acceleration at the end of the curve. Overall, findings suggest that velocity and acceleration control among drivers with ASD may be comparable to that of TD drivers. Previous simulator work has indicated that adolescent and young adult drivers with ASD exhibit similar control of acceleration and speed variability relative to adult TD drivers (Cox et al., 2017). Further, examinations of driving records have found that young drivers with ASD have significantly lower rates of moving violations (Curry et al., 2021). In studies that have detailed differences in acceleration magnitude and control (Cox et al., 2016) and speed regulation (Bishop et al., 2018; Classen, Monahan, & Wang, 2013) among drivers with ASD, participants were asked to complete cognitive tasks while driving (e.g., following a lead car, response inhibition tasks, hazard avoidance, divided attention tasks). As this study did not present hazards or distractions during curve negotiation, this may explain discrepant findings. Moreover, this discrepancy underscores that tactical and operational skills may suffer among individuals with ASD during more complex driving scenarios where cognitive demands have exceeded the load capacity of the driver, but may otherwise be comparable to TD peers (Curry et al., 2021).

Steering Behavior Hypotheses

When negotiating the right curve, the steering behavior patterns of drivers with ASD in this sample were similar to those of TD drivers and aligned with profiles typically seen in the TD curve negotiation literature (Kolekar et al., 2018). Namely, steering wheel activity and lateral vehicle movement were highest around apex entry and exit and lowest at curve entry points. Contrary to hypotheses, no significant differences in steering control emerged between drivers with and without ASD. This may be due to the high variability in performance relative to the small sample size, and consequently overlapping 95% confidence intervals. These metrics require further investigation to better understand if group differences in steering control consistently emerge during curve negotiation.

Steering wheel activity and lateral vehicle movement of drivers with ASD did not significantly differ from TD drivers during left curve negotiation. However, steering behavior profiles differed substantially during this curve relative to the right curve, especially with respect to variables implicated in steering wheel activity. From the approach tangent to apex exit, participants' steering wheel activity during the left curve was similar to activity during the right curve; however, activity dramatically increased when negotiating the curve exit and exit tangent. This substantial increase in steering wheel activity toward the end of the curve can be understood best when viewed in conjunction with vehicle dynamic performance during the left curve.

Participants entered the left curve at an increased velocity and subsequently coasted at a reduced speed throughout the curve. During this time, the variability of steering angle, mean steering velocity, and variability in steering velocity remained stable, and values were similar across groups. In naturalistic curve negotiation, drivers accelerate through curves in order to offset the lateral acceleration forces that push the vehicle outward. When drivers do not accelerate and/or when they decelerate to reduce their speed, this increases the lateral forces on the vehicle and may cause it to skid (Comte & Jamson, 2000). Driving simulators are unable to simulate the physical sensation of lateral acceleration vestibular feedback on a participant; however, the simulated environment is programmed in such a way to respond to driver behaviors with visually realistic consequences. Participants likely experienced the visual cue of a potential skid and subsequently engaged in larger steering oscillations in an attempt to stabilize the vehicle. Indeed, when analyzing the steering range at curve exit and exit tangent, values are up to five times larger than the ranges observed during the previous segments. These kinds of compensatory steering responses are common toward the end of a curve regardless of negotiation speed, but drivers use especially large oscillations when more stabilization and correction are needed (Bonneson, 2000).

Interestingly, despite comparable mean values for steering angle variability, steering velocity, and steering velocity variability across groups, group differences in the rate of steering reversals and the rate of lane exceedances emerged at different curve segments. Specifically, during left curve negotiation, the rate of steering reversals for the ASD group relative to the TD group at the approach tangent was significantly higher at every curve segment except for the exit tangent. The rate of lane exceedances for the ASD group relative to the TD group at curve entry was higher at curve exit. Of note, the percent of time spent out of the lane did not differ significantly between groups, indicating that these lane exceedances may have been brief but recurrent during this segment.

This pattern potentially indicates a difference in steering control to regain lateral lane position stability during unexpected periods of driving instability, wherein drivers with ASD may make more steering reversals in an attempt to maintain or regain vehicle control. When coupled with an increased SDLP, increased steering wheel activity has been specifically implicated during driving tasks that involve both cognitive and visual task load (Engström et al., 2005). Moreover, steering reversal rate has been proposed as a sensitive metric for capturing the effects of both cognitive and visual load on driving performance, whereas other steering wheel metrics (e.g., SD steering angle) are only sensitive to cognitive load tasks (Markkula & Engström, 2006). Considering that the simulator relies heavily on visual cues to signal potential adverse events, the left curve may have become a more visually-loaded task once the environment began simulating a skid, and differences in steering reversal across groups reflect the ability to recover from this load. Previous work has examined where drivers with ASD allocate visual attention while driving under normal conditions (Chee et al., 2019; Cox et al., 2020); however, there are no previous studies comparing curve driving behaviors in environments that differ visual and technical complexity.

Qualitative research lends support to complex driving situations being more challenging for individuals with ASD. Young adult drivers with ASD report experiencing more difficulty handling unexpected changes while driving (Almberg et al., 2017), and parents of drivers with ASD have also observed these difficulties in their children (Cox et al., 2012). Further, naturalistic driving data indicate higher variability in lane positioning when negotiating roundabouts (Van Zuylen et al., 2020), and crash report data suggest that, when drivers with ASD experience a collision, they are more likely to crash in complex driving scenarios such as U-turns and left-hand turns across intersections (Curry et al., 2021). Increased steering reversals and lane exceedances may put drivers at a higher risk for run off road crashes during challenging curves. Additional investigation is needed to discern if difficulties navigating complex driving situations are a function of challenges with motor planning and execution, differences in gaze patterns, visuomotor integration difficulties, and/or other underlying processes, as well as the extent to which degrees and types of complexity affect driving behavior among those with ASD.

It is important to note that observed differences in driving behavior profiles across curves are likely due to differences in the driving environment rather than a fundamental difference in right versus left curve negotiation approach. Prior to navigating the right curve, participants drove through a residential area wherein they were expected to avoid hazards. This could have primed participants to be more cautious when driving through the curve. Further, this curve was presented early on in the experimental drive, and it was the first time participants had driven through a right-hand residential curve. Conversely, the left curve was the second left-hand residential curve participants had experienced (the first occurred during the practice drive), and it was presented toward the end of the experimental drive. Participants may have felt more comfortable with left-hand curves in the environment, and/or they could have been experiencing fatigue and wanted the experiment to terminate more quickly. In addition, participants drove through a hazardless freeway straightaway prior to entering the left curve; this likely accounts for the increase in speed when entering the approach tangent.

Limitations and Future Directions

As has already been alluded, this study had limitations that add caveats to interpretation while also illuminating areas of improvement for future research. The small sample size limited both generalizability and statistical power; future studies should recruit a more robust sample to minimize the impact of error variance in obscuring potential group differences. ASD symptomatology was measured via a brief self-report assessment, and confirmation of diagnostic status for inclusion in the ASD group relied on participant report. Although participants provided proof of prior diagnostic testing from a healthcare provider, diagnostic measures were not standardized across participants. Future work should use rigorous gold-standard measures (e.g., ADOS-2 [Lord et al., 2012] and ADI-R [Rutter et al., 2003]) to confirm ASD diagnosis, catalog diagnostically relevant symptomatology, and allow for standard comparison across studies.

As this study involved secondary data analyses, certain limitations resulted from design constraints that could not be retroactively altered. For example, there were only 2 horizontal curves (1 right, 1 left) programmed into the virtual environment, presentation order was fixed, and the environment prior to the curve differed between the right and left curves. Future studies interested in analyzing curve-specific variables would benefit from a counterbalanced design with multiple, standardized presentations of both right and left curves. This would also allow for comparison of curve negotiation patterns due to curve direction, as previous studies have found that strategies may differ during right-hand horizontal curves (Othman et al., 2010), and that these curves result in more crashes (Othman et al., 2009). Last, hand positioning was not standardized during curve negotiation. While this allowed for a more natural use of the steering wheel, it is unclear if some participants turned with one hand, both hands, or by using hand-over-hand steering. As arm posture has been shown to alter aspects of steering control among TD drivers (Schmidt et al., 2015), future studies may want to incorporate standardized hand position into the study design, or analyze how different hand positions alter control among drivers with ASD.

Some limitations were also inherent to driving simulator studies. For example, simulator sickness, or "physical discomfort experienced when 'driving' a simulated vehicle that is caused by incompatible signals from visual, auditory, and motion systems," (Classen et al., 2011) is a well-documented limitation of simulator research. Individuals who are most susceptible include those 70 years and older in age and women (Classen et al., 2011); however, our sample excluded 3 male participants due to simulator sickness, 2 of whom had ASD. Because simulator sickness is caused by processing discrepant stimuli in sensory domains known to be different in ASD (e.g., visual, motor, vestibular), it is conceivable that participants with ASD in our sample were more susceptible to experiencing simulator sickness due to sensory sensitivity. The rates and underlying mechanisms of simulator sickness among individuals with ASD have not been explicitly explored in the literature. Prior driving simulator studies have found that the frequency of simulator sickness among individuals with ASD is similar that of TD individuals (Bishop et al., 2017; Chee et al., 2019; Cox et al., 2020; Reimer et al., 2013). However, future studies may wish to assess for a history of motion sickness prior to enrollment to further reduce attrition risk. Finally, during naturalistic curve negotiation, lateral acceleration cues are crucial for drivers to control longitudinal velocity and acceleration. However, a known limitation in driver simulator work, particularly in simulators restricted to a pitch motion base, is reduced vestibular feedback, especially with respect to lateral acceleration. This limits ecological validity when analyzing curve performance. A naturalistic study design would allow quantification of curve metrics while accounting for vestibular cues.

These results suggest that driving behavior differences among individuals with ASD may be contingent on the complexity of roadway situations during curve negotiation. Future studies should more clearly elucidate the factors involved in adding complexity during curves (e.g., radius size of curve, hazard presentation during curve negotiation, winding curves in multiple succession), as well as potential underlying mechanisms of differential curve performance such as processing speed (Van Zuylen et al., 2020), working memory (Cox et al., 2016), and risk-taking tendencies (Wilde, 2001). Integration of eye tracking during curve negotiation would also allow for analysis of gaze fixation to explain the role of attention allocation in complex driving environments.

No roadway environment is 100% predictable, so a crucial aspect of driver safety is the ability to effectively navigate unexpected or complicated scenarios. A more robust understanding of the unique difficulties experienced by drivers with ASD during complex driving situations could allow for the development of targeted driver interventions and training protocols. The findings herein suggest that training the steering control aspects of curve negotiation may be beneficial for this population, specifically in scenarios where an unexpected roadway event occurs. Driving simulators can provide a unique training environment to teach these behaviors, as they allow for safe, repeated practice of difficult maneuvers in a variety of driving environments without the risk of collision on a real road. In particular, simulators may be particularly beneficial tools to practice foundational driving skills for drivers with ASD who are apprehensive about practicing on a real road (Ross et al., 2018).

Cox and colleagues (2017) developed a promising pilot driving simulation training focused on improving aspects of tactical performance (e.g., maintaining and refining lane positioning, use of mirrors, hazard detection, etc.) among young drivers with ASD. This training involved multiple hour-long sessions where a particular tactical skill would be modeled by a trainer, the teen would practice the modeled skill, and the trainer would provide explicit feedback and support. When compared to self-taught driving training using a driving instruction manual, virtual reality driving simulation training produced significant improvements in tactical control – including steering control – compared to a baseline assessment prior to intervention. Their results support additional research dedicated to identifying driving environments and scenarios that may put drivers with ASD at a higher risk on the road in order to further fine-tune and individualize these training paradigms. This could allow for more individuals with ASD to learn and hone the skills needed to drive safely, thereby reducing the licensure disparity between adults with ASD and the general population (Curry et al., 2018) and allowing for increased vocational and employment opportunities, participation in social activities, and improved quality of life.

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APPENDIX A

PRINCIPAL COMPONENTS ANALYSIS WITH ALL CONTINUOUS VARIABLES

Variable	1	2	3
Mean Longitudinal Acceleration	-.27	.19	**.57**
SD Longitudinal Acceleration	-.03	**.85**	-.03
Mean Longitudinal Velocity	.03	**.48**	-.08
SD Longitudinal Velocity	-.02	.24	**.79**
Percent of Time Out of Lane	-.05	**.59**	-.28
Steering Range	**.98**	.05	.03
SDLP	-.03	**.81**	-.10
SD Steering Angle	**.96**	.05	.04
Mean Steering Velocity	**.96**	.01	.06
SD Steering Velocity	**.97**	.02	.03

Note. Component loadings greater than .30 are in bold. No rotation was applied.

APPENDIX B

REPEATED MEASURES ANOVA MAIN EFFECTS AND INTERACTIONS FOR RAW STEERING-RELATED VARIABLES

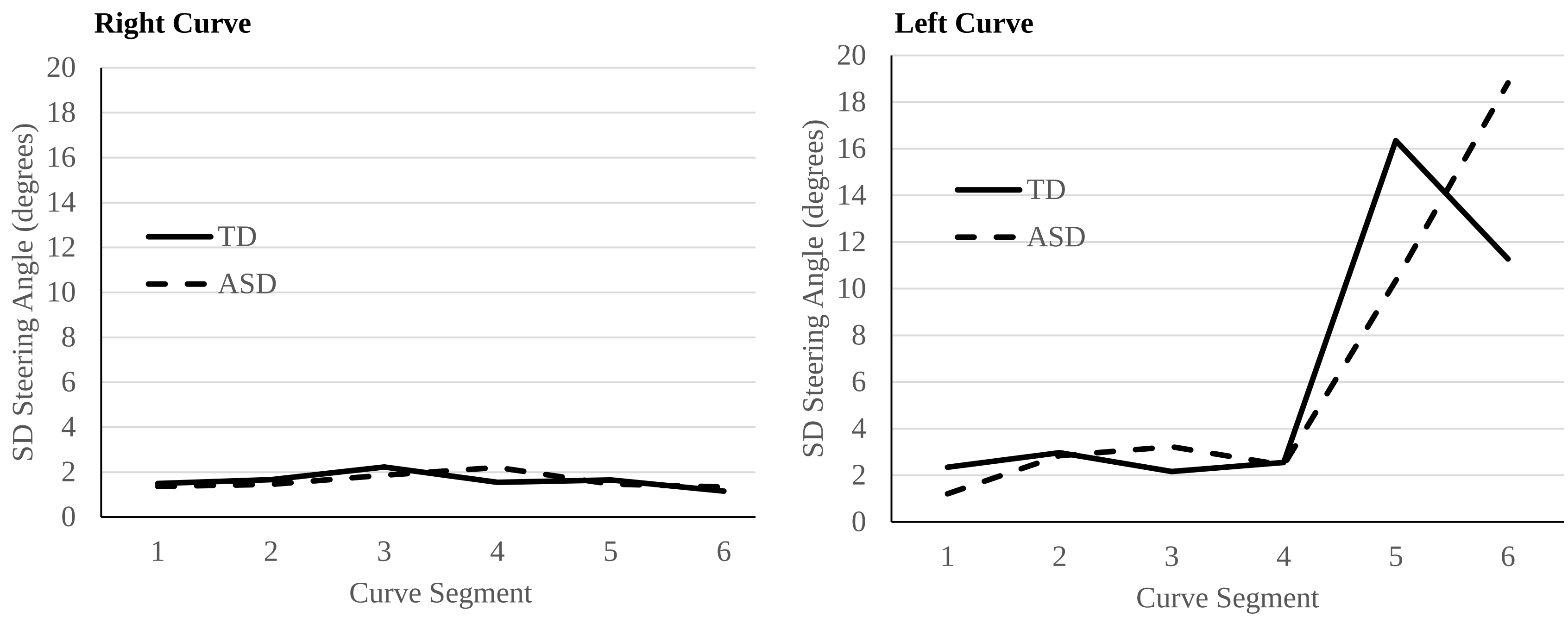
Variable	Factor	Right Curve			Left Curve		
		F	p	η_p^2	F	p	η_p^2
SD Steering Angle	Group	$F(1, 27) = 0.00$	.98	.00	$F(1, 25) = 0.00$	.95	.00
	Segment	$F(4, 108.00) = 1.90$	.12	.07	$F(1.52, 37.89) = 4.72$	.02*	.16
	Group x Segment	$F(4, 108.00) = 0.76$	.55	.03	$F(1.52, 37.89) = 0.61$	.51	.02
M Steering Velocity	Group	$F(1, 27) = 1.95$	.17	.07	$F(1, 27) = 0.12$	.73	.01
	Segment	$F(3.76, 101.37) = 1.82$	.14	.06	$F(1.14, 30.67) = 6.35$	.01*	.19
	Group x Segment	$F(3.76, 101.37) = 0.43$	.78	.02	$F(1.14, 30.67) = 0.07$	.82	.00
SD Steering Velocity	Group	$F(1, 25) = 2.70$	.11	.10	$F(1, 26) = 0.36$	.56	.01
	Segment	$F(4.20, 104.95) = 3.43$	.01*	.12	$F(1.12, 29.19) = 5.9$	.02*	.19
	Group x Segment	$F(4.20, 104.95) = 0.25$	.92	.01	$F(1.12, 29.19) = .25$	.65	.01
Steering Range	Group	$F(1, 27) = 0.00$	.98	.00	$F(1, 26) = 0.23$	.63	.01
	Segment	$F(4.21, 113.65) = 3.31$	.01*	.11	$F(1.28, 33.36) = 6.03$	.01*	.19
	Group x Segment	$F(4.21, 113.65) = 0.66$	.63	.02	$F(1.28, 33.36) = .34$	.62	.01
SDLP	Group	$F(1, 28) = 1.22$	.28	.04	$F(1, 27) = 1.88$	.18	.07
	Segment	$F(3.76, 105.21) = 25.67$	<.001***	.48	$F(3.61, 97.53) = 33.29$	<.001***	.55
	Group x Segment	$F(3.76, 105.21) = 0.56$	.68	.02	$F(3.61, 97.53) = 0.99$	.41	.04
Percent of Time Out of Lane	Group	$F(1, 29) = 0.86$	.36	.03	$F(1, 29) = .16$	.70	.01
	Segment	$F(4.15, 120.43) = 8.64$	<.001***	.23	$F(4.55, 132.05) = 2.73$	.03*	.09
	Group x Segment	$F(4.15, 120.43) = 1.49$	.21	.05	$F(4.55, 132.05) = 1.15$	.34	.04

Note. Covariates are not included in reported data, as neither measure of driving experience was a significant predictor of steering performance

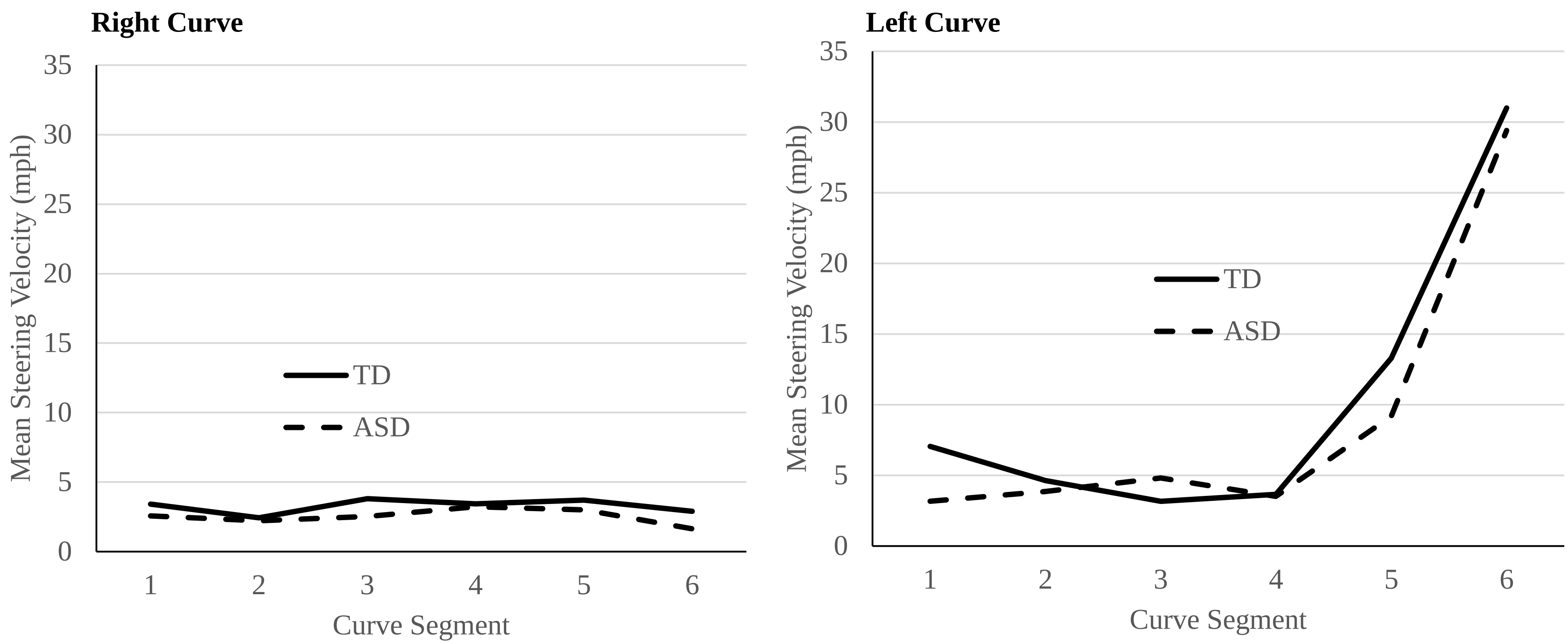
*$p < .05$. **$p < .01$. ***$p < .001$.

APPENDIX C

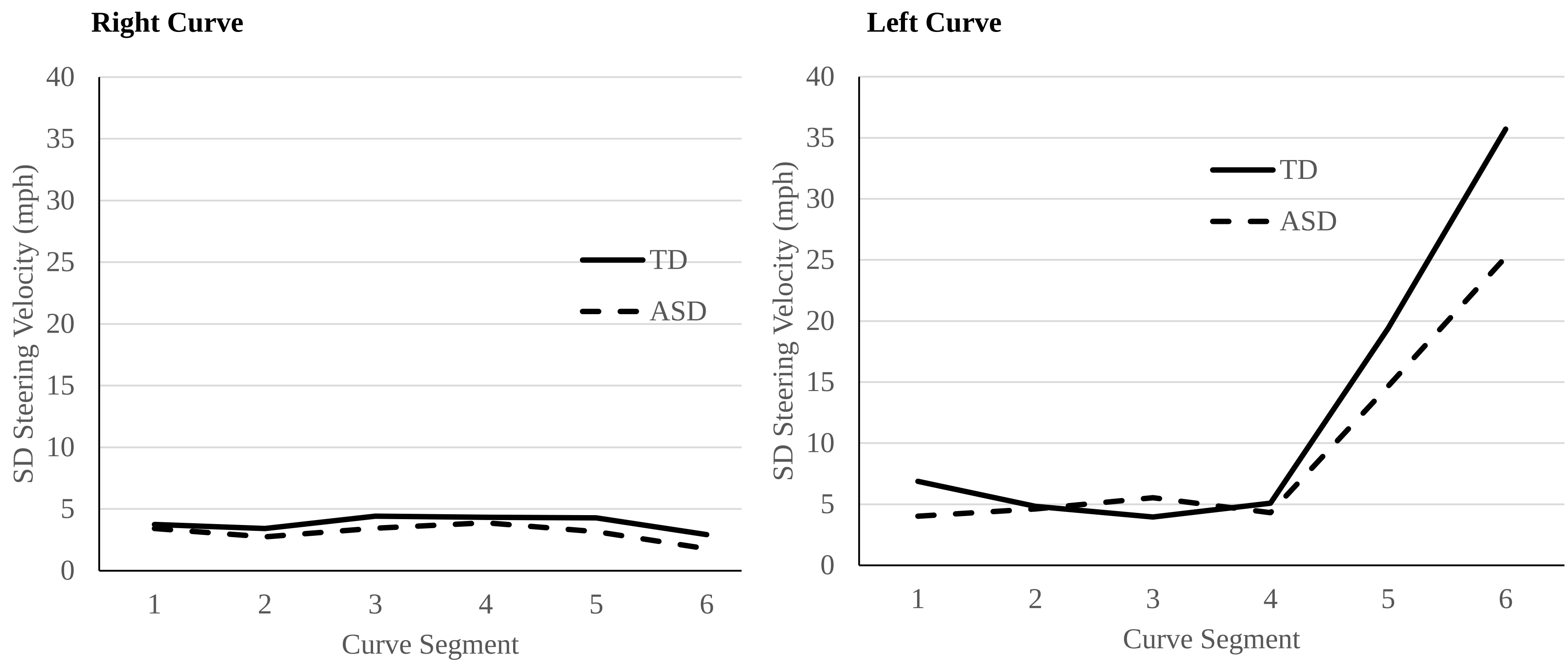
STEERING-RELATED BEHAVIORS BY GROUP ACROSS CURVE SEGMENTS USING RAW STEERING-RELATED VARIABLES



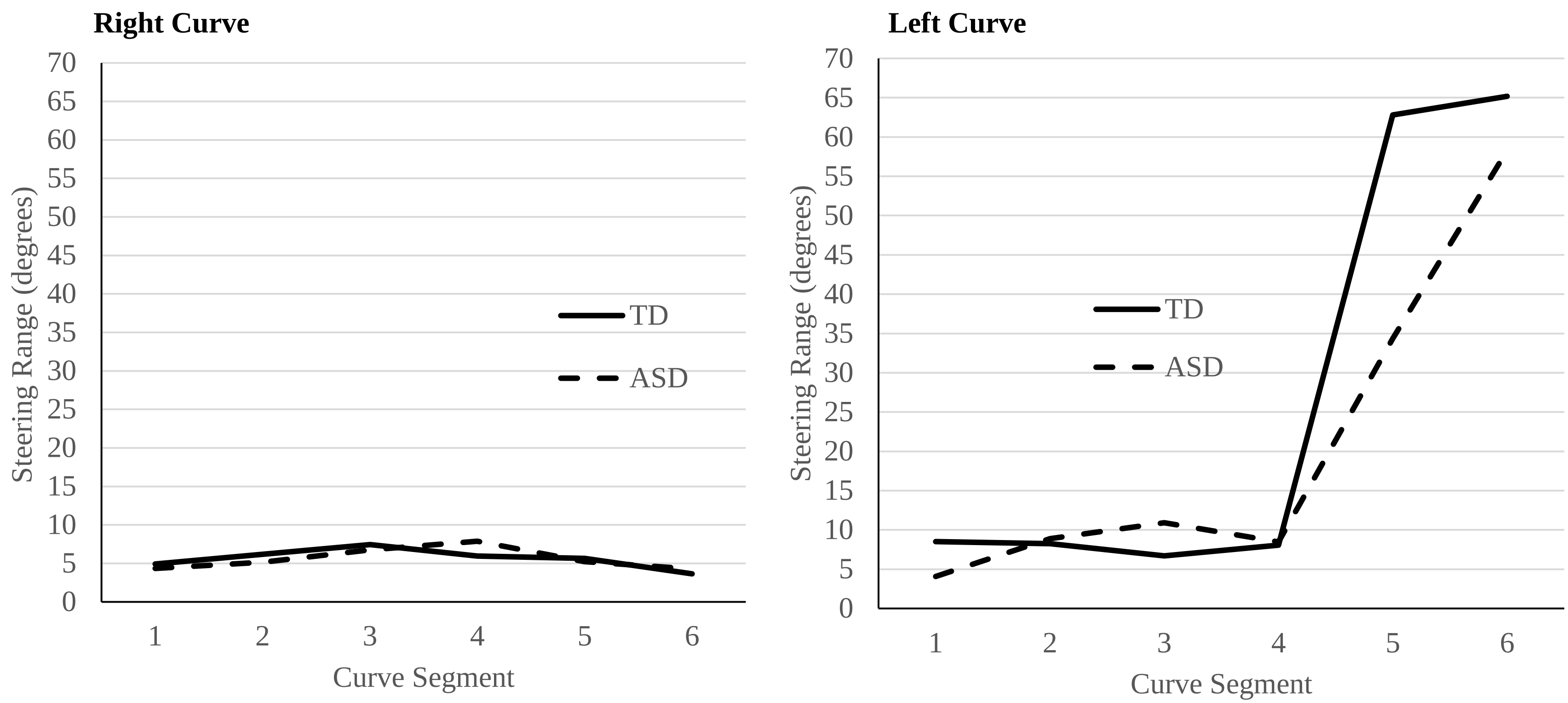
Note. SD steering angle at each segment for the right and left curves is shown above. 1 = approach tangent, 2 = curve entry, 3 = apex entry, 4 = apex exit, 5 = curve exit, 6 = exit tangent.



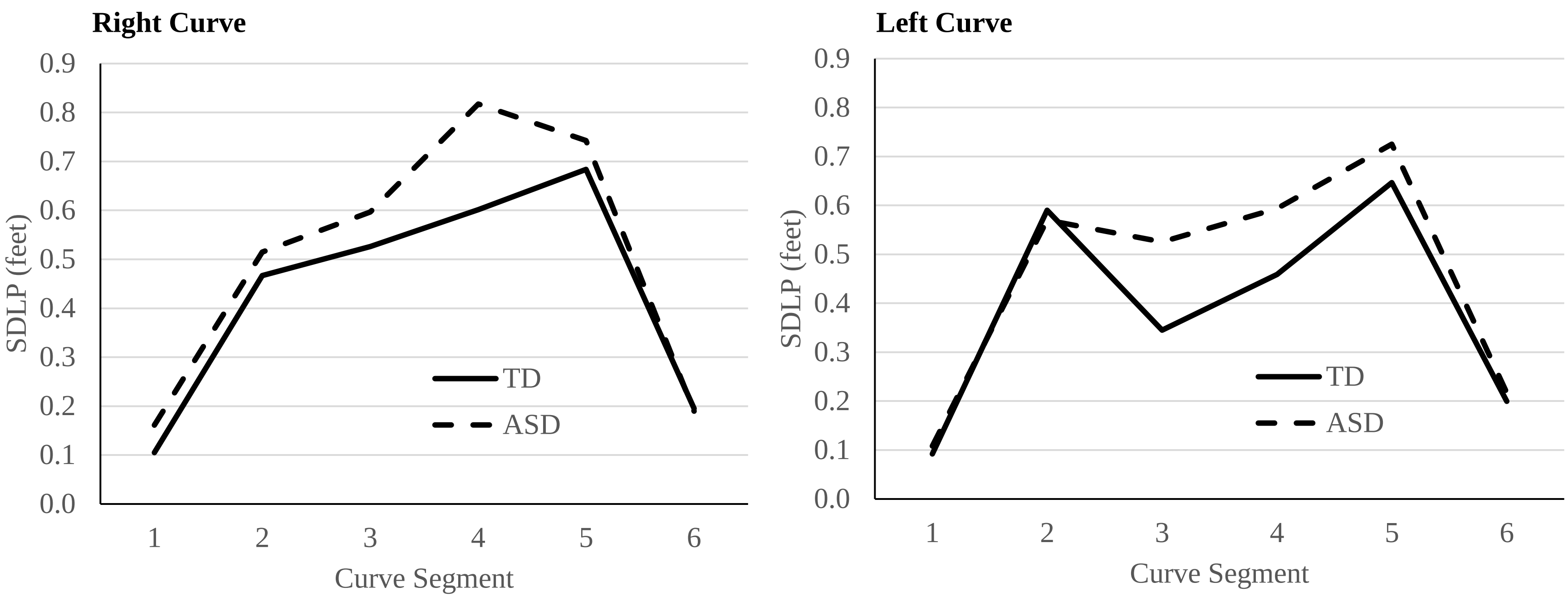
Note. Mean steering velocity at each segment for the right and left curves is shown above. 1 = approach tangent, 2 = curve entry, 3 = apex entry, 4 = apex exit, 5 = curve exit, 6 = exit tangent.



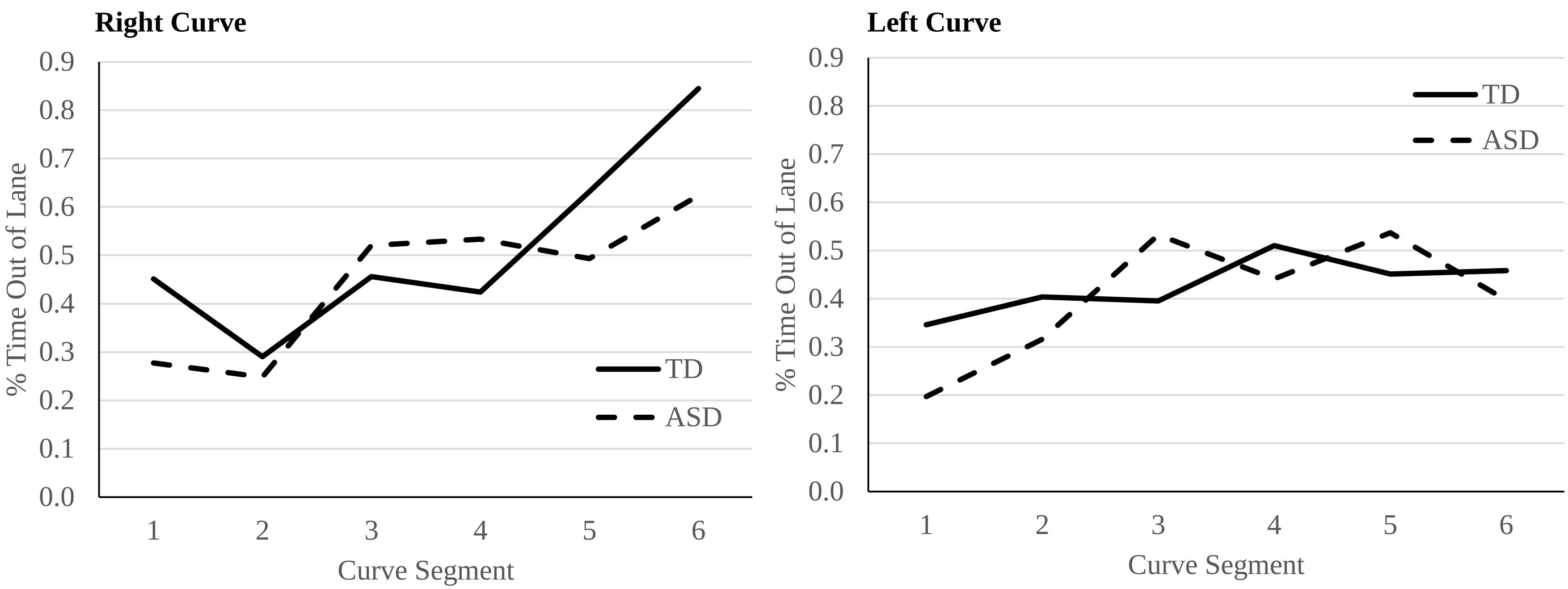
Note. SD steering velocity at each segment for the right and left curves is shown above. 1 = approach tangent, 2 = curve entry, 3 = apex entry, 4 = apex exit, 5 = curve exit, 6 = exit tangent.



Note. Steering range at each segment for the right and left curves is shown above. 1 = approach tangent, 2 = curve entry, 3 = apex entry, 4 = apex exit, 5 = curve exit, 6 = exit tangent.



Note. SDLP at each segment for the right and left curves is shown above. 1 = approach tangent, 2 = curve entry, 3 = apex entry, 4 = apex exit, 5 = curve exit, 6 = exit tangent.



Note. Percent of time spent out of the lane at each segment for the right and left curves is shown above. 1 = approach tangent, 2 = curve entry, 3 = apex entry, 4 = apex exit, 5 = curve exit, 6 = exit tangent.