Article

OTJR: Occupational Therapy Journal of Research
2025, Vol. 45(2) 219–231

DOI: 10.1177/15394492241271115
journals.sagepub.com/home/otj
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A Randomized Controlled Trial on Automated Vehicle Technologies for Drivers With Parkinson's Disease

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Abstract
Parkinson's disease (PD) negatively affects driver fitness. Few studies document the benefits of in-vehicle information systems (IVIS) and advanced-driver assistance systems (ADAS), the focus of this study, for drivers with PD. This study quantified the impact of IVIS and ADAS on the number of on-road driving errors. Drivers with PD (N = 107) drove a vehicle equipped with IVIS and ADAS in traffic. The activation of IVIS and ADAS resulted in fewer driver errors. Specifically, adaptive cruise control reduced the number of speeding errors on the highway. Bradykinesia correlated with driving errors with deactivated systems. Memory impairments correlated with the total number of driving errors with activated systems. Impairments in executive function and visuospatial ability were associated with more errors during system deactivation. IVIS and ADAS reduced the total number of driving errors for PD drivers; ameliorated effects of individual variations; but memory declines posed a challenge while using these technologies.

Plain Language Summary
A randomized controlled trial study of self-driving in-vehicle technologies on driver fitness for people with Parkinson's disease
This study investigated the effects of in-vehicle information systems (IVIS) and advanced driver-assistance systems (ADAS) on the driver fitness of individuals with Parkinson's disease (PD). Notably, 107 drivers with PD drove a vehicle equipped with IVIS and ADAS. The results showed that activating these systems led to fewer speeding errors on the highway. The study identified correlations between bradykinesia, executive function, visuospatial ability, and increased errors with deactivated systems, where memory impairments correlated with increased driving errors during system activation. Although IVIS and ADAS had a positive overall effect, challenges related to memory decline existed when these technologies were in use.

Keywords
Parkinson's disease, automated in-vehicle technologies, on-road, driving errors, driver rehabilitation

Introduction

Worldwide, about 7.5 million persons live with Parkinson's disease (PD), a number predicted to increase to 13 million by 2040 (Dorsey & Bloem, 2018). PD is an age-related, progressive, neurodegenerative disorder characterized by resting tremor, rigidity, bradykinesia, and postural instability (Jankovic & Tolosa, 2007). In addition to the motor symptoms associated with PD, non-motor concerns, including visual deficits, cognitive decline, depression, emotional and behavioral impairments, sleep disorders, and autonomic dysfunction are a significant source of disability (Riggeal et al., 2007; Uc et al., 2005). Men are 1.5 times more likely than women to be diagnosed with PD, and the incidence of PD increases with age (Parkinson's Foundation, n.d.). These clinical features of PD also affect an individual's ability to perform activities of daily living and instrumental activities of daily living (e.g., driving) (World Health Organization, 2001).

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Drivers with PD have worse driving performance and increased crash risks compared with those without PD. Visual (binocular acuity and contrast sensitivity), visual perceptual (visual scanning and speed of processing), cognitive (set-shifting and cognitive flexibility), and motor impairments (psychomotor speed, reaction time, slowed walking, and fine motor movements) (Amick et al., 2007; Classen et al., 2011; Crizzle et al., 2012; Devos et al., 2015; Dubinsky et al., 1991; Uc et al., 2005, 2006; 2009; Worringham et al., 2006) contribute to their impaired driving performance. A meta-analysis of 50 studies, reported the odds of on-the-road test failure as 6.16 times higher, and the odds of simulator crashes as 2.63 times higher for people with PD (Thompson et al., 2018). After conducting an evidence-based review (27 studies), Devos et al. (2015) found that a combination of visual, cognitive, and motor deficits leads to impaired driving skills in PD. Moreover, compared to age- and gender-matched controls, participants with mild-to-moderate stages of PD (M_{age} = 68) were more likely to fail a driving assessment. Although fitness to drive impairments increases crash risk (Meindorfner et al., 2005; Uc & Rizzo, 2008; Uitti, 2009), even in the early stages of PD (Crizzle et al., 2012; Devos et al., 2015), self-reported crashes did not differ between people with PD and healthy controls (HC) (Thompson et al., 2018), despite controlling for age, sex, driving exposure, and disease severity differences based on disease duration and motor symptoms. Taken together, the literature provides persuasive evidence for substantive driving impairment in PD.

Although highly autonomous vehicles have the potential to prevent crashes among those with PD, their deployment and market penetration are still decades away (Bhuiyan, 2016; National Highway Traffic Safety Administration, 2017). Automated in-vehicle technologies hold opportunities to mitigate impaired driving in PD drivers. Specifically, SAE International (2016) indicates six levels (Levels 0–5) of automation. Level 0 (warnings and momentary assistance to the driver), Level 1 (steering or brake/ acceleration support to the driver), and Level 2 (steering and brake/acceleration support to the driver) may benefit the driver with PD to overcome cognitive workload. Level 3 systems (driver must take control of the vehicle when prompted) are still not widely available. Level 4 (automated system can perform all driving functions under certain conditions) and Level 5 (automated system can perform all driving functions, under all conditions) may yield multiple benefits related to transportation equity for people with PD but is currently a future reality.

In-vehicle information systems (IVIS, e.g., lane departure warning [LDW]) provide warnings to drivers about surrounding road conditions but do not intervene with the driving task (Wilschut, 2009). Advanced driver-assistance systems (ADAS, e.g., adaptive cruise control [ACC]) are integrated systems that can provide vehicle control (Wilschut, 2009). Because speed and lane position are compromised in people with PD, ACC will maintain vehicle following distance while LDWs and steering assist can assist with maintaining lane position—and as such prevent speeding, slowing, or lane departure errors, and may prevent crashes (Classen et al., 2014; Devos et al., 2015). A 24-study scoping review examined the effect of IVIS and ADAS on the driving performance of older adults. Results indicated IVIS had improved safety of the driving task (e.g., faster responses) if cognitive workload was not compromised, or the driver was not over-reliant on the feature (Wilschut, 2009). Pertaining to ADAS features, findings indicate improved safety and comfort, including speed control, lane maintenance, braking, and decreased driving stress. Only one study (Dotzauer, 2015) involved people with PD and demonstrated improved speed control with the use of a Heads-Up Display system (IVIS). Therefore, drivers with PD may benefit from in-vehicle technologies to mitigate impaired driving skills, decrease driving errors, and enhance their fitness to drive abilities, but no such studies have yet been conducted.

People with PD may not be able to compensate for the progressive loss of functional visual, cognitive, motor, and other sensory abilities. The current driver rehabilitation interventions are less than optimal to ensure their continued driving (Edwards et al., 2013; Uc et al., 2011); are only tested on a limited number of drivers with PD (Uc et al., 2011); and although cognitive (Edwards et al., 2013) and simulator training are feasible (Devos et al., 2016), results are not generalizable to ensure that PD drivers can return to driving safely. The IVIS and ADAS features are already integrated in vehicles manufactured in recent years, and researchers may examine the impact of these features on driving performance of people with PD. If the features are beneficial for drivers with PD, then educational programs may be developed to keep them on the road longer and safer.

The purpose of this study is to quantify the effect of IVIS and ADAS on driving safety, operationalized as the number of driving errors made by people with PD, in an on-road test vehicle. Based on previously published work, evidence supports that speeding errors, lane exceedances, and signaling errors predicted failing an on-road assessment, in drivers with PD (Classen et al., 2014). The hypothesis is that drivers with PD will demonstrate fewer total number of driving errors (primary outcome) and fewer speeding, lane exceedances, and signaling errors, when driving on-road with automated in-vehicle technology. Our work (Classen et al., 2019b) and that of others (Brookhuis et al., 2001; Davidse, 2006; Devos et al., 2015; Dotzauer, 2015; Martin & Elefteriadou, 2010) have shown that drivers with PD make more driving errors, on-road (Classen et al., 2014; Uc et al., 2005, 2006, 2009, 2011), when compared with HC. The study also compares driving speed maintenance and control (median, standard deviation [*SD*], and peak speeds) during highway driving with and without IVIS and ADAS. This inquiry is addressing the above objective via *an efficacy study of on-road errors* detected by the assessment data of the driver rehabilitation specialist (DRS) and in-vehicle technologies. Because cognitive and physical impairments contribute to worse performance during driving, this study also examines how demographics and individual differences in cognitive and physical ability, as measured through clinical measures, affect the number of errors made while driving with and without IVIS and ADAS. Challenges encountered during the study recruitment and analysis through an analysis of participant attrition between initial screening and enrollment in the study are also discussed.

Method

This project was approved by the University's Institutional Review Board (IRB#: 202002321), and each participant signed an informed consent form prior to study participation and were reimbursed US$30.00 for study completion. The study was registered in clinicaltrials.gov (registration #: NCT04660500)

Participants and Consort Chart

Participants (N = 107; M_{age} = 68.0 years, SD = 8.28 years) completed the study. Inclusion criteria included diagnosis by a neurologist/movement disorder specialist with clinically probable or established PD according to the Movement Disorders Society (MDS) criteria; mild or moderate disease severity based on motor symptoms (MDS-Unified PD Rating Scale for motor symptoms); age between 35 and 85 years; currently driving with a valid driver's license and meets the Florida state requirement for visual acuity; lives independently in the community; and are proficient in reading/speaking English. Participants were excluded if they had a Montreal Cognitive Assessment (MoCA) score of 20 or lower indicating moderate cognitive impairment (Nasreddine et al., 2005); concurrent neurological conditions (e.g., stroke, uncontrolled seizures, dementia); uncontrolled, severe psychiatric symptoms (e.g., psychoses or severe anxiety), or physical conditions (e.g., missing limbs) that would preclude full participation; use of psychotropic medications that may negatively affect mental or physical functioning at the discretion of the investigator, due to direct or side effects; severe, unpredictable motor fluctuations; and severe sleep difficulties.

Participants were recruited through direct referrals from movement disorder neurologists affiliated with the UF Fixel Institute for Neurological Diseases and referrals from outside physicians recruited via local PD patient support groups, mailing lists, and outreach events which were verified by our team of UF neurologists. The information pertaining to the study flow, referral, screening, intake, and dropout of participants are provided in the CONSORT chart, in Figure 1.

Design

This efficacy study used a one-group within-subjects design where participants with PD completed two drives, each drive under a different IVIS/ADAS condition: activated versus deactivated (main experimental variable). Before the actual on-road drive, participants were not knowledgeable of the order of presentation of the *activated* versus *deactivated* conditions, as the order was randomly allocated to participants prior to enrollment. During the actual drive, participants became knowledgeable of the *activated* versus *deactivated* conditions.

Equipment

A Toyota Camry XLE 2019 model featuring the Toyota Safety Sense 2.0 IVIS and ADAS was used. The IVIS systems include LDW, which alerts the driver when the vehicle drifts out of the lane through visual and auditory alerts, and blind spot monitor (BSM), which monitors for vehicles in the car's blind spots and provides a visual indicator on the side mirrors when a vehicle is present. The ADAS features include the ACC, which provides cruise control and maintenance of vehicle headway distances at speeds above 32 mph, and lane steering assist (LSA), which provides gentle steering assistance to bring the vehicle back into the lane when it begins to drift out of the lane. Participants drove on both local suburban two-lane and four-lane roadways and a divided highway (Figure 2). The primary outcome variable was the number of driving errors made under the two experimental conditions (system activated vs. deactivated). The recorded errors included overspeeding errors (5 mph over the posted speed limit), underspeeding errors (5 mph under the posted speed limit or below the flow of traffic), encroachment errors (lane departures into oncoming traffic), wide errors (lane departures away from oncoming traffic), and signaling errors (failure to activate or deactivate the turn signal). The DRS assessed these errors on the straight sections of the roads and excluded any errors made during turns as the vehicle systems used in the study did not function during turns.

An auxiliary passenger side brake was installed to allow for the DRS to assume control when needed. To capture when the IVIS and ADAS systems were active, cameras were installed to capture the car's multi-information display, where ACC, LDW, and LSA alerts were provided, and of the side mirrors, where BSM alerts were provided. A computer vision model was trained to detect and identify when the systems were active and each event was checked by a human researcher. A detailed description of the apparatus can be found in a previously published feasibility study (Classen et al., 2022).

Procedure

Each participant was screened according to the study criteria. On meeting the telephone screening criteria, participants were scheduled for the in-person assessment, provided written consent, and were enrolled in the study. Individuals who scored below 20 on the MoCA were withdrawn from the study (Nasreddine et al., 2005).

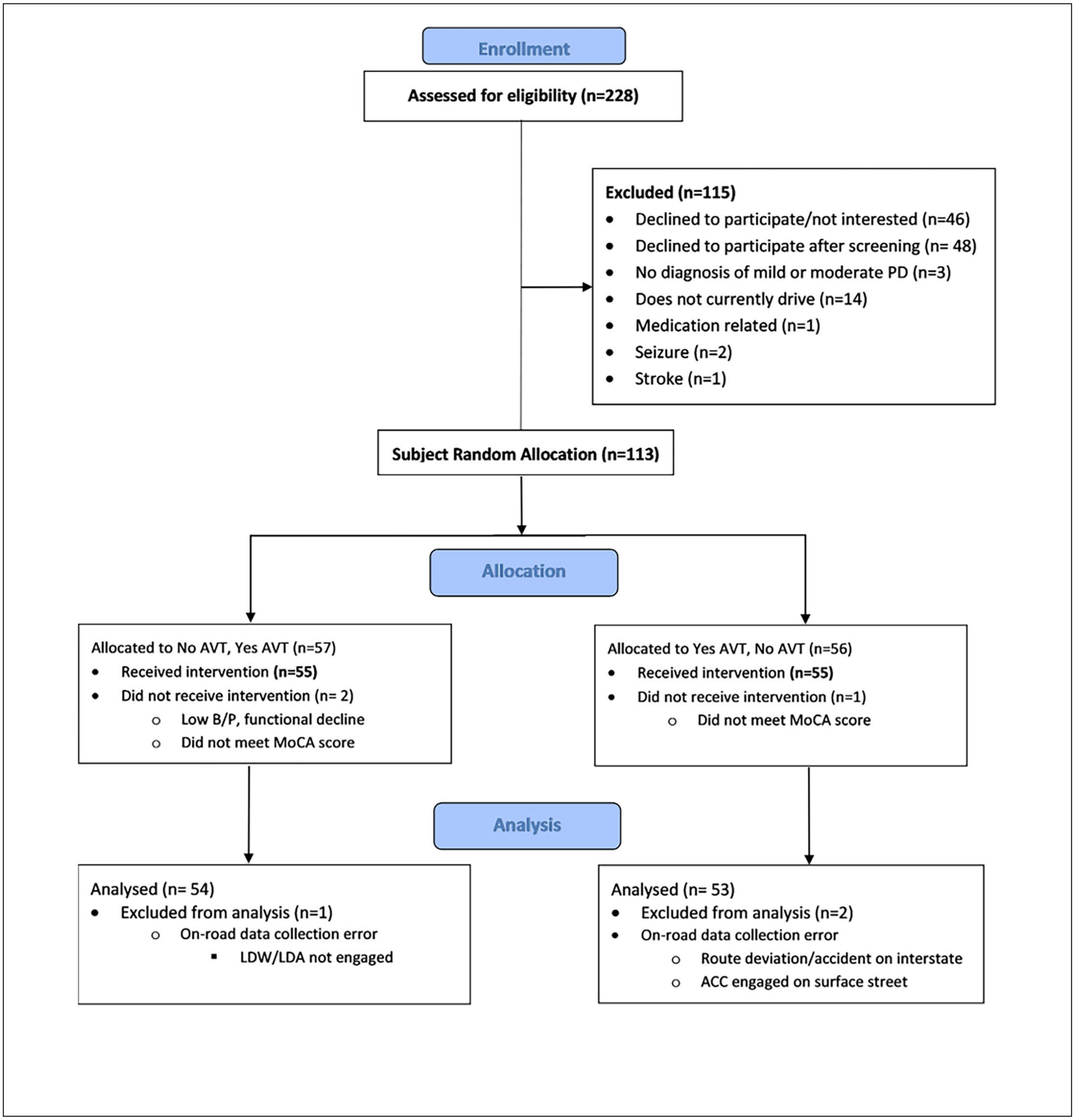

Figure 1. CONSORT Diagram Showing Participant Flow.

Next, participants completed a battery of clinical assessments, including the Snellen chart, Optec 2500 Visual Analyzer for field of view (Stereo Optical Company Inc., 2007). Eligible participants then filled in a demographic questionnaire. The MDS-UPDRS Part 3 and 4 (Goetz et al., 2023) and the Modified Hoehn and Yahr (MH&Y) disease severity scale (Goetz et al., 2004) was completed by a movement disorder neurologist. The DRS oriented participants to the test vehicle, checked for participant proficiency in managing the vehicle's controls, and provided a verbal explanation of IVIS and ADAS. Each participant completed a standardized 7-min acclimation drive in the parking lot, to ensure comfort and competency with the vehicle and its controls, prior to the on-road drive. The driving segment of this study was completed in the *ON* state of medications (i.e., within 4 hr of taking the anti-Parkinsonian drugs).

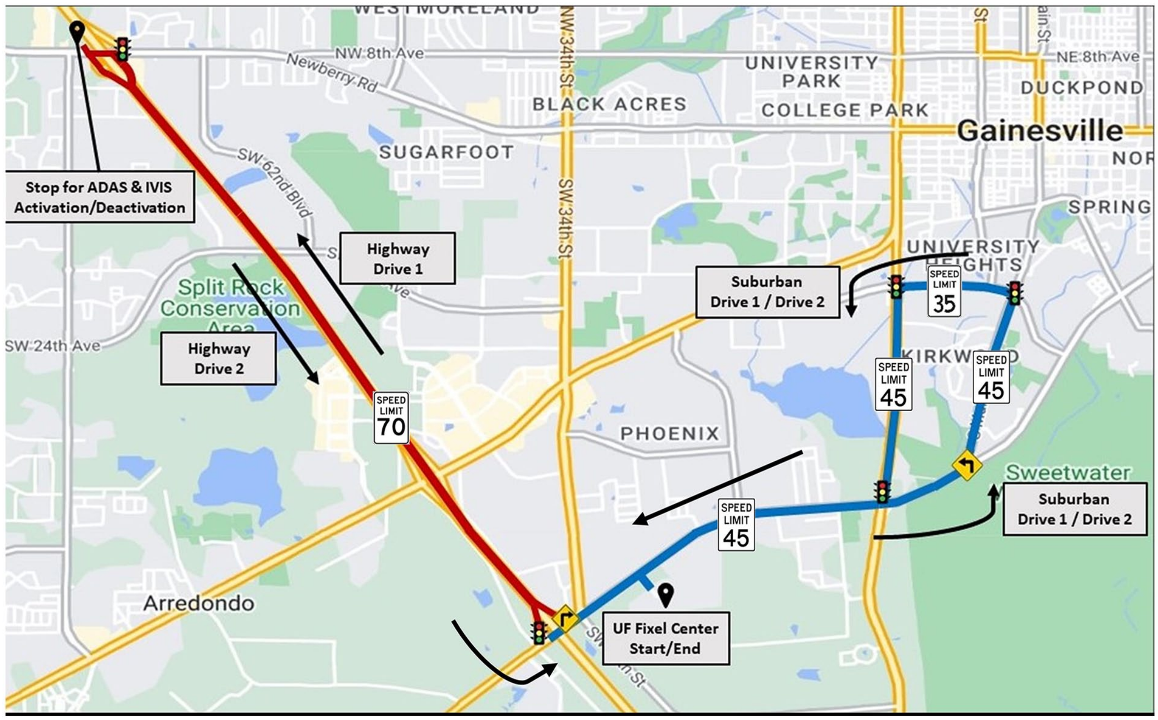

Figure 2. Driving Route Displayed in the Google Map (Blue = Suburban Route, Red = Highway Route), Total Driven Distance: 25.19 Miles, Total Drive 1 Distance: 12.49 Miles (49.6%), Total Drive 2 Distance: 12.69 Miles (50.4%).

To control for order and learning effects, we used two congruent drives on one route (Figure 2). Half of the participants started with the driver-assistance systems activated for the first half of the drive and the systems deactivated during the second half of the drives; the other participants had the order of the system activations reversed. The drive started in the parking lot, leading to a suburban area, and a divided highway section. At the half-way point of the route, after the highway section, participants pulled over in a parking lot and the DRS activated/deactivated the driver-assistance systems, depending on the order of the randomization. During the system-activated condition, the LDW, LSA, and BSM were active in both the suburban and highway road segments, while the ACC was only active during the highway drive. To ensure consistency, once the car had reached an appropriate speed on the highway, the DRS activated the ACC. The details of the road course were published in a previous article (Classen et al., 2022). Essentially, the 26.5-mile road course had 27 controlled and 88 uncontrolled intersections, 10 left and 5 right turns. The speed limits varied between 35 and 45 mph on two-lane and four-lane roadways and were 70 mph on the divided highway. All drives occurred outside of peak traffic hours and in the absence of heavy rain or fog.

The DRS sat in the passenger seat, provided navigation guidance to the drivers, monitored the road safety, and activated/deactivated the IVIS and ADAS per study protocol. Moreover, the DRS recorded driving errors and documented the type and frequency of errors for each road segment on a standardized recording form.

Power Analysis

The study was powered to quantify the effect of IVIS and ADAS on the number of driving errors made by participants when driving with automated in-vehicle technology. The main hypothesis is that people with PD who drive with versus without automated in-vehicle technology will make fewer total number of driving errors. We have based this power analysis on our previous work (Classen et al., 2014). Specifically, the assumption is that people with PD will at least make a similar number of errors as healthy controls when they drive on-road with autonomous in-vehicle technology. The PD drivers will have a Pearson's correlation of .5 between the two conditions (IVIS and ADAS [de]activated). The effect size was determined by subtracting the mean number of on-road driving errors of healthy controls (24.08, SD = 12.38) from that of PD drivers (31.99, SD = 22.03), resulting in a difference of 7.91 errors (Classen et al., 2014). With an assumed correlation of .5, the SD for the difference is 22.01. Our calculation, based on a two-sided one-sample t-test, necessitates a sample size of 105 to achieve a 95.4% power, with an alpha of .05 and a beta of .046.

Data Management and Analysis

The screening to enrollment analysis examined differences between those who enrolled and completed the study versus those who were screened eligible but decided not to enroll. Age disparities between the groups were examined using independent two-sample t-tests. To compare gender distributions and residential settings (rural versus urban), we used chi-square tests for independence. Finally, we compared the driving distance to the location (categorical) using Fisher's exact test. We also examined the participants' reasons for not enrolling in the study.

Error data collected by the DRS were analyzed by system condition (activated vs. deactivated) and driving environment (suburban vs. highway). Within each driving environment, the effects of the IVIS and ADAS were evaluated using a Wilcoxon signed-rank test. Differences in speed variables were evaluated using paired t-tests. Spearman's rho correlations were used to understand the effects of individual differences within the sample (e.g., age, motor, and cognitive differences) on the number of driving errors when the IVIS and ADAS were (de)activated. Analyses were conducted using R version 4.2.1 (2022-06-23) (R Core Team, 2022).

The total and subtest scores of the MoCA and the MDS-UPDRS Part 3 were computed. Specifically, the MoCA subtests include Visuospatial/Executive and Memory Index Score (MIS), whereas the MDS-UPDRS Part 3 subtests include rigidity, bradykinesia, and tremor. The MoCA-MIS, which has a total score of 15 points, was calculated based on the participant's ability to recall the five words from the memory test after 5 min. For each word, three points were awarded if the participant was able to recall without any cues, two points for recall with a category cue, and one point for recall with a multi-choice cue. The MDS-UPDRS 3-Rigidity score was determined by the summation of subcategories 3.3, while the MDS-UPDRS 3-Bradykinesia score was computed by adding up subcategories 3.4–3.8. The MDS-UPDRS 3-Tremor score was calculated by summing up subcategories 3.15–3.18. All data were stored and managed in REDCap (Harris et al., 2009).

Some technical issues were encountered during data collection that led to incomplete or missing data. In total, 34 participants did not have the LSA system active during the system activated condition; however, all other IVIS and ADAS, including the LDW were present. Four participants had issues with the side mirror cameras, resulting in some missing BSM data. Finally, one participant had missing speed data due to a telemetry system error. These data points were excluded from the analysis for the relevant variables.

Results

Screening to Enrollment Analysis

We analyzed differences between individuals who were referred to the study, screened eligible, yet declined participation, and those who were enrolled and participated in the study. Demographic data are shown in Table 1.

No differences were found between those who enrolled and those who were not enrolled for age, gender, and driving distance to the experiment. The proportion of individuals from rural versus urban areas differed between those who were and were not enrolled, $p < .001$. Among those who did not enroll, almost half were from rural areas.

Among participants who did not complete the study, the most frequently cited reason was a lack of interest. Others had health-related concerns, encompassing issues such as fractures, family member's health concerns, worries about the COVID-19 variant (the study was run between 2021 and 2023), travel burdens, schedule logistics, and hesitation about the driving portion of the study. Even though the researchers assured study participants that no reporting will occur to the Department of Motor Vehicles (DMV), participants were concerned about losing their driver's license, reporting to the DMV, and apprehension about highway driving and unfamiliar roads. Taken together the findings suggest that those who were living in rural areas and those who experienced a burden from potentially participating in the study did not enroll—with the team having to double up on recruitment to meet the study's sample size.

Participant Demographics

Table 2 presents a summary of participant demographics along with cognitive (MoCA) and motor (MDS-UPDRS Part 3) scores. PD severity, as measured by the "ON" MH&Y Scale ranged from 1 to 3. Specifically, 9 participants scored 1.0, 11 scored 1.5, 81 scored 2.0, 4 scored 2.5, and 2 scored 3.0 indicating a range of mild-to-moderate severity on the MH&Y scale. Overall, 97 participants (90.65%) had prior experience with either IVIS, ADAS, or both.

Total Number of Driving Errors

The total number of driving errors was lower when the systems were activated versus deactivated $p < .01$ (Table 3). Specifically, the total number of errors made while driving on highways was lower when the systems, including the ACC, were active versus inactive $p < .01$. In contrast, the total driving errors in the suburban segment when the automation systems were activated which did not include the ACC, were not significantly different than with the deactivated condition. As such, the findings indicate that ACC when activated (vs. deactivated) benefits drivers on the highway section, but not in the suburban area.

Types of Errors

As seen in Table 3, both overspeeding and underspeeding errors significantly decreased as a result of IVIS and ADAS use during the drive's highway portion, where the ACC was

Table 1. Comparison of Demographics of Enrolled Versus Declined to Enroll Participants.

Variable		Enrolled (N = 113)	Declined to participate after screening (N = 48)	Comparison between enrolled and declined to participate
Age	Mean	68.03	67.15	$t(148.38) = 0.63$, $p = .53$, *ns*
	SD	8.28	7.93	
Gender	Male	N = 79, 73.1%	N = 35, 72.92%	$\chi^2(1) = 0.00$, $p = 1$, *ns*
	Female	N = 29, 26.9%	N = 13, 27.08%	
Rural vs. urban*	Rural	***N* = 9, 7.96%**	***N* = 17, 48.5%%**	$\mathbf{\chi^2(1) = 27.69, p < .001^*}$
	Urban	***N* = 104, 92.04%**	***N* = 18, 51.43%**	
Driving distance to UF Fixel (miles)	0–50	N = 47, 41.59%	N = 9, 23.08%	Fisher's exact test, $p = .145$, *ns*
	50–100	N = 27, 23.89%	N = 8, 20.51%	
	100–150	N = 20, 17.70%	N = 11, 28.21%	
	150–200	N = 6, 5.31%	N = 3, 7.69%	
	>200	N = 13, 11.50%	N = 8, 20.5%	

*and **bolded values** comparisons denote significant differences.

Table 2. Participant Demographics and Clinical Characteristics.

Measure	First quartile	Median	Third quartile	Range
Age (years)	62	69	74	42
MoCA[a]	24	26	28	9
MoCA—executive/visuospatial[b]	4	4	5	4
MoCA—MIS[c]	11	13	14	12
ON—MDS-UPDRS—rigidity score[d]	2	3	5	11
MDS-UPDRS—upper extremity bradykinesia score[d]	3	5	8	15
MDS-UPDRS—lower extremity bradykinesia score[d]	2	3	5	13
ON—MDS-UPDRS—tremor score[d]	0	2	6	15
ON—MDS-UPDRS—part III total score[d]	16	22	29	53

[a]MoCA: Montreal Cognitive Assessment, lower scores indicate greater cognitive impairment, scale ranges from 0 to 30.
[b]Lower scores indicate greater impairment, scale ranges from 1 to 5.
[c]Memory Index Score (MIS), lower scores indicate greater impairment, scale ranges from 0 to 15.
[d]Higher scores indicate greater impairment, measures were taken with medication in an ON state, scale ranges from 0 to 20.

Table 3. The Number of Driving Errors Across Driving Segments (Highway Versus Suburban) and System Conditions (Activated Versus Deactivated) Showing Means and Standard Deviations.

	Highway and suburban			Highway			Suburban		
Driving errors	System activated	System deactivated	Wilcoxon test	System activated	System deactivated	Wilcoxon test	System activated	System deactivated	Wilcoxon test
Overspeeding	1.44 (1.52)	1.47 (1.41)	V = 1,079.5 ***p* = .71**	**0.01 (0.09)**	**0.07 (0.25)**	**V = 4.5** ***p* = *.041****	1.43 (1.50)	1.40 (1.37)	V = 1,235.5 p = .97
Underspeeding	**1.88 (2.14)**	**2.66 (2.37)**	**V = 819** ***p* < *.001****	**0.27 (0.52)**	**0.88 (0.89)**	**V = 198** ***p* < *.001****	1.61 (1.94)	1.79 (1.98)	V = 987.5 p = .25
Encroach	0.87 (1.28)	0.89 (1.49)	V = 841 p = .57	0.28 (0.56)	0.21 (0.43)	V = 112.5 p = .13	0.59 (1.12)	0.68 (1.29)	V = 766.5 p = .79
Wide	1.52 (2.52)	1.38 (1.97)	V = 1,361 p = .97	0.79 (1.35)	0.71 (1.28)	V = 717 p = .56	0.73 (1.50)	0.67 (1.16)	V = 732.5 p = .93
Signaling	0.24 (0.53)	0.38 (1.26)	V = 256 p = .45	0.08 (0.28)	0.09 (0.32)	V = 30 p = .80	0.16 (0.42)	0.29 (1.19)	V = 126 p = .47
Total driving errors	**5.95 (4.21)**	**6.79 (3.62)**	**V = 1,626** ***p* < *.01****	**1.44 (1.61)**	**1.95 (1.75)**	**V = 859.5** ***p* < *.01****	4.51 (3.21)	4.83 (2.86)	V = 1,781 p = .21

*and **bolded values** denote significant differences.

Table 4. Number of IVIS and ADAS Activations During the System Active Condition (Means and Standard Deviations).

	Suburban and highway		Highway		Suburban	
Automation systems	Left	Right	Left	Right	Left	Right
Lane steering assist (LSA), $n = 70$	1.59 (1.74)	2.34 (2.70)	0.64 (0.87)	1.04 (1.38)	0.94 (1.29)	1.30 (2.11)
Lane departure warning (LDW), $n = 106$	0.87 (1.36)	1.37 (2.55)	0.38 (0.77)	0.82 (1.42)	0.49 (1.04)	0.55 (1.42)
Blind spot monitoring (BSM), left $n = 104$, right $n = 106$	16.13 (8.00)	9.39 (5.18)	7.85 (4.88)	0.85 (1.61)	7.89 (5.19)	8.56 (4.72)

Table 5. Spearman's Rho Correlations Between Individual Difference Factors and the Total Number of Driving Errors With the Systems Activated or Deactivated.

Individual difference factors ($n = 107$)	System activated	System deactivated
Age	0.19 ($p = .053$)	0.09 ($p = .333$)
MDS-UPDRS[a]—rigidity	0.03 ($p = .762$)	0.12 ($p = .219$)
MDS-UPDRS—tremor	−0.07 ($p = .489$)	−0.003 ($p = .978$)
MDS-UPDRS—upper extremity bradykinesia	0.18 ($p = .0609$)	**0.22 ($p = .0261$*)**
MDS-UPDRS—lower extremity bradykinesia	0.04 ($p = .689$)	**0.21 ($p = .0293$*)**
MoCA[b]—total	**−0.23 ($p = .0185$*)**	**−0.26 ($p = .00634$*)**
MoCA—executive/visuospatial	−0.11 ($p = .28$)	**−0.23 ($p = .018$*)**
MoCA—MIS[c]	**−0.24 ($p = .011$*)**	−0.14 ($p = .143$)

[a]MDS-UPDRS = Unified Parkinson's Disease Rating Scale.
[b]MoCA = Montreal Cognitive Assessment.
[c]MIS = Memory Index Score.
*and **bolded values** denote significant correlations, $p < .05$.

in use. The overall number of speeding errors was low across all conditions, especially for overspeeding. In contrast, the use of the systems did not significantly affect speeding errors during the drive's suburban portion, where the ACC was not active. Therefore, the ACC reduced the number of speeding errors and benefited the drivers more with highway versus suburban driving.

To better understand speed maintenance and control on the highway (70 mph speed limit), the median, peak, and *SD* of speeds were calculated for each participant. The median speed was higher when the automation systems were activated ($M = 64.31$ mph, $SD = 5.33$) than when they were deactivated ($M = 62.64$ mph, $SD = 7.21$), $t(105) = 2.67$, $p < .01$. The peak speed when the automation systems were activated ($M = 69.53$ mph, $SD = 3.46$) was lower than the peak speed when the automation systems were deactivated ($M = 70.70$ mph, $SD = 3.72$), $t(105) = 3.27$, $p < .01$. Taken together, the activated (vs. deactivated) ACC helped participants maintain more consistent and appropriate speeds, as shown by the higher median speed and lower peak speeds. However, the *SD* of the speed when the automation systems were activated ($M = 14.04$ mph, $SD = 1.70$) was not significantly different than when the automation systems were deactivated ($M = 13.86$ mph, $SD = 2.06$, $t(105) = −0.66$, $p = .51$). The similar variability in speeds was likely influenced by the lead vehicle following the abilities of the ACC, which would match the speed of the lead vehicle to maintain a set headway time. Thus, the activation (vs. deactivation) of the ACC played a significant role in maintaining consistent speeds on highways, despite the observed variation in the *SD* measure.

For the other error types, none of the lane departure (encroach and wide) nor signaling differed when IVIS and ADAS were activated versus deactivated. Table 4 shows the average number of times IVIS and ADAS alerted or intervened during the system-activated conditions. These system activations, while low, would have resulted in a different driving experience between the system activated and deactivated portions of the drive. So, the findings indicate no differences in driving errors, as expected between the activated and deactivated conditions, for lane departure (encroach and wide) and signaling, which is somewhat surprising.

Effect of Individual Differences on Error Counts

Demographic and individual differences, that is, cognitive and motor ability, may influence driving errors (Amick et al., 2007; Crizzle et al., 2012; Devos et al., 2015; Dubinsky et al., 1991; Uc et al., 2006). Spearman's rho correlations were conducted between these factors and the total number of driving errors when IVIS and ADAS were activated versus deactivated (Table 5). Significant correlations indicate that the corresponding individual difference factor influenced the likelihood of driving errors.

Overall, the effect of the factors was stronger when IVIS and ADAS were deactivated versus activated, as shown by the stronger correlations and greater number of significant factors. Notably, with the systems deactivated, there was a significant relationship between total driving errors and both MDS-UPDRS upper ($\rho = .22$) and lower extremity ($\rho = .21$) bradykinesia scores. In contrast, when the systems were active, neither of the correlations reached significance, though upper extremity bradykinesia had a stronger and significant correlation to driving errors than lower extremity bradykinesia scores. Rigidity and tremor scores were not significantly correlated with driving errors in either system status. These findings suggest that the IVIS and ADAS benefited the drivers with PD to help mitigate or curtail driving errors associated with upper and lower extremity bradykinesia.

Furthermore, a significant negative correlation existed between overall MoCA scores and driving errors both when the systems were activated and deactivated. A closer examination revealed that this relationship varied depending on the system's status. Specifically, driving errors were inversely correlated with scores on the MoCA's executive/visuospatial subscale when the systems were deactivated. In contrast, when the systems were activated, the MIS subscale of the MoCA showed a significant negative correlation with the total number of driving errors. These findings suggest that with the deactivated system, impairments in executive function and visuospatial ability resulted in a greater number of driving errors. However, it was the impairments in the MIS that resulted in a greater total number of driving errors when the systems were active.

Discussion

We examined the efficacy of IVIS and ADAS during on-road driving errors in 107 participants with PD as detected by in-vehicle kinematics and the assessment data of the DRS.

Overall, the IVIS and ADAS resulted in fewer driver errors compared to when the systems were not active. The differences were largely due to changes in the number of overspeeding and underspeeding errors made on the highway, where the ACC was active. This is noteworthy as it indicates that ACC may mitigate the cognitive load which can result in speeding errors. Particularly, the ACC may prevent the need for visual scanning and speed of processing (Classen et al., 2011; Uc et al., 2006; Worringham et al., 2006) and cognitive impairments (Amick et al., 2007; Dubinsky et al., 1991; Worringham et al., 2006) present in drivers with PD. The results also found differences in speed measures during this highway portion that further corroborate the types of speeding errors identified, as participants appeared to have higher median speeds when the systems were active, which would have helped prevent underspeeding errors, while also having lower peak speeds, avoiding overspeeding errors. The ACC takes over speed maintenance, which is both a perceptual/cognitive (headway and looming detection) (Amick et al., 2007; Classen et al., 2011; Dubinsky et al., 1991; Uc et al., 2006; Worringham et al., 2006) and motor (pedal control) task (Classen et al., 2011; Crizzle et al., 2012; Devos et al., 2015; Worringham et al., 2006). These cognitive and motor performance deficits greatly impair driving ability (Classen et al., 2014; Uc et al., 2009, 2011) in drivers with PD—which appears to be mitigated by the use of ACC, and as such provide benefit for drivers with PD.

In suburban driving, we did not see the expected safety benefits from the IVIS and ADAS. This was likely due to the ACC not being in use in this portion of the drive. Instead, warnings and alerts from IVIS were the primary safety mechanism, which would still require drivers to notice and physically react to the warnings. Particularly with LDWs, an error already occurs before the warning is triggered, leading to a higher error count despite the active systems. Future studies could examine the severity of lane departures in terms of their duration and deviation, which may be more sensitive to the benefits provided by these safety systems.

The results also suggest that the IVIS and ADAS helped to ameliorate the decrements due to individual difference factors. Motor impairments were less influential when IVIS and ADAS were present, and this was likely due to the presence of the ACC that took over physical control of the speed, resulting in less pedal control by the driver (Classen et al., 2014; Uc et al., 2009, 2011) This interpretation is further strengthened given the low correlation between lower extremity bradykinesia scores and driver error ($\rho = .04$), which may have a greater impact on pedal control, than upper extremity scores ($\rho = 0.18$), which is more likely to impact steering movements. As described earlier, the number of lane departure errors was not significantly reduced by IVIS and ADAS, likely due to our current experiments reliance on IVIS alerts rather than direct control of the vehicle, and it is likely that a lane centering system, which would take over steering activities, would further improve the benefits of vehicle automation for individuals with greater motor impairments.

Interestingly, the rigidity and tremor sub-scores of the MDS-UPDRS were not significantly correlated to driving errors when the systems were active and when they were deactivated. Moreover, and consistent with the prevailing literature, all participants completed the on-road drive in the "ON" medication state, which may explain the lack of differences due to the motor control factors (Classen et al., 2011, 2014; Devos et al., 2015).

Cognitive factors played a large role in the number of errors made by the participants. The extant literature on cognition and on-road driving errors has not yet documented the relationship with subcomponents of the MoCA and driving errors. Although we are not surprised, the findings are confirming our clinical expectations (Classen & Holmes, 2013; Devos et al., 2016, 2007; Uc et al., 2006). Although the overall MoCA score was significantly correlated with driving errors, the analysis suggests that different cognitive domains affect driving errors with and without the vehicle automation systems. When the systems were not active, decrements in executive function and visuospatial ability resulted in a greater number of driving errors. This is not surprising given the heavy visuospatial attention demands in driving. However, it was decrements in the MIS that resulted in a greater total number of driving errors when the systems were active. Issues with short-term delay recall, as measured by the MIS, may result in several challenges when using in-vehicle technology, including difficulties in remembering the functionality of the systems or how to respond when an alert is received that are not present during driving without the activation of IVIS and ADAS.

Finally, people with PD have *tactical driving skill impairments* (Devos et al., 2015), such that during a driving task, functions related to steering, braking, accelerating, stopping, or controlling the vehicle may be impaired. Specifically, drivers with PD may have speeds too high or too low when they need to maintain a safe headway distance, or when they need to anticipate and adjust to traffic stimuli (Classen et al., 2019a; Devos et al., 2015; Edwards et al., 2013; Uc et al., 2005, 2009). Thus, the activated ACC function mitigated the number of errors, particularly during the highway drive, and benefited drivers with PD. Specifically, the ACC automatically adjusts the speed of the vehicle, so the driver with PD can overcome set-shifting, judging of gaps, memory recall, and processing speed demands (Classen et al., 2019a; Devos et al., 2015; Edwards et al., 2013; Uc et al., 2005, 2009) to maintain a safe headway distance and to maintain their vehicle within the flow of traffic.

Although the current results highlight promising on-road benefits of ADAS and IVIS, their long-term advantages require further study. Numerous challenges exist for the safe use of these technologies, particularly their unreliability when operating outside the specific conditions for which they were designed (American Automobile Association, 2022; Cummings & Bauchwitz, 2022, 2024). On-going research suggests that specialized training (Zheng et al., 2023) and interface design solutions (Beller et al., 2013) can enhance the safe usage of these systems, though many drivers remain unaware of their vehicles' capabilities and limitations (DeGuzman & Donmez, 2021; Greenwood et al., 2022). Research has shown benefits of providing specific types of training for older adults (Zheng et al., 2023), and research should further examine the best ways to teach individuals with PD about the limitations of these systems. Furthermore, the use of ADAS and IVIS may affect long-term behavior of individuals with PD due to having drivers adopt speeds that they may not be comfortable with, or by increasing their reliance of these technologies. For example, removing ADAS after short-term exposure deteriorates driving performance in drivers with PD (Dotzauer, 2015). These results, again, suggest that the use of ADAS and IVIS has benefits, but will require driver education, improved systems design, and careful planning to improve the safety of drivers with PD.

Furthermore, this study also analyzed differences between enrolled participants and those individuals who were referred but not enrolled. Both groups were of similar age and predominantly male. Most enrolled participants were from urban communities, whereas those who were not enrolled were almost evenly split between urban and rural communities. Although there was not a significant difference in travel distance to the study site (UF Fixel), participants did report travel and logistical considerations influencing their decision to participate. The proportion of rural participants was lower among the enrolled group compared with the non-enrolled group. This suggests either a lower perceived utility of IVIS and ADAS in rural areas or inadequate recruitment efforts targeting these communities. Future studies should aim to increase recruitment from rural areas to explore potential differences in demographics and technology preferences.

Limitations

Study limitations include self-selection bias, convenience sampling from one major PD treatment clinic, participants' apprehension about participating in an on-road study, demographic and geographic factors that restrict the generalizability of the findings, and the researchers not including IVIS and ADAS use as eligibility criteria. For 37 participants, the LSA system, was not active. Although this may have resulted in more lane departure errors when the systems were active than would be expected, these systems do not take over steering control as completely as lane centering or lane keeping systems.

Strengths

Technology-based interventions extend fitness to drive the abilities of drivers with PD, modify driver behavior (Classen et al., 2022), mitigate the PD-related factors affecting driving (Classen et al., 2014; Uc et al., 2006), and improve community mobility. Such automated technologies, including the use of IVIS and ADAS, are now a reality—and this study is the first to provide evidence for the efficacy of these in-vehicle technologies. We have used state-of-the-art technology, kinematics, data from the on-board DRS, and team science to quantify the efficacy of IVIS and ADAS on driver fitness.

Conclusion and Future Work

We have demonstrated how IVIS and ADAS reduced the driving errors for individuals with PD, particularly during highway driving. Moreover, although the effects of age, cognitive, and physical ability can be partially ameliorated by this technology, memory declines may challenge drivers with PD to use these technologies effectively.

Future studies could examine the severity of lane departures in terms of their duration and deviation, which may be more sensitive to the benefits provided by these safety systems. In addition, studies assessing driving performance in the "ON" and "OFF" motor states may provide additional insight into the contribution of specific motor concerns to driving ability. Drivers with prominent motor fluctuations and dyskinesia were excluded from the study. Evaluation of advanced therapies including deep brain stimulation and Duopa (a prescription medication used to treat advance PD) is unclear, and further studies in drivers with advanced PD are needed.

Acknowledgments

The authors thank the Institute for Driving, Activity, Participation, and Technology (I-DAPT), Human Systems Engineering Laboratory, and the Norman Fixel Institute for Neurological Diseases at the University of Florida, which provided infrastructure and support for this study.

Author Contributions

The authors confirm contribution to the paper as follows:
Sherrilene Classen: Conceptualization, Methodology, Participant recruitment, Writing—draft preparation, Writing—reviewing and editing, Supervision.
Wayne C. W. Giang: Conceptualization, Methodology, Data collection, Investigation, Writing—draft preparation, Writing—reviewing and editing.
Albraa Rajkhan: Data collection, Data processing, Data visualization, Writing—draft preparation, Writing—reviewing and editing.
Haolan Zheng: Data collection, Data processing, Data visualization, Writing—draft preparation, Writing—reviewing and editing.
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Bhavana Patel: Participant recruitment, Data collection, Writing—reviewing and editing.
Sandra Winter: Data collection, Writing—draft preparation, supervision.
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Yuan Li: Data collection, Participant recruitment and enrollment, Writing—draft preparation.
Adolfo Ramirez-Zamora: Participant recruitment, Data collection, Investigation, Writing—reviewing and editing.

Declaration of Conflicting Interests

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

Funding

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This randomized controlled trial (RCT) was funded by the National Institute on Disability, Independent Living, and Rehabilitation Research (NIDILRR, award no. 90IFRE0035, PI: Classen). NIDILRR had no role in the design or execution of the protocol.

Trial Registration

The study was registered in clinicaltrials.gov (registration #: NCT04660500).

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