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## **DRIVING BEHAVIOUR OF DRIVERS WITH MILD COGNITIVE IMPAIRMENT AND ALZHEIMER'S DISEASE: A DRIVING SIMULATOR STUDY**

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## **ABSTRACT**

The objective of this research is the analysis of the driving performance of drivers with Alzheimer's disease (AD) and Mild Cognitive Impairment (MCI), on the basis of a driving simulator experiment, in which healthy "control" drivers and impaired drivers drive in different driving scenarios, following a thorough neurological and neuropsychological assessment of all participants. The driving scenarios include driving in rural and urban areas in low and high traffic volumes. The driving performance of drivers impaired by the examined pathologies (AD and MCI) is compared to that of healthy controls by means of Repeated Measures General Linear Modeling techniques. In this paper a sample of 75 participants is analyzed. Various driving performance measures are examined, including speed, lateral position, steering angle, headway, reaction time at unexpected events etc., some in terms of their mean values and some in both their mean values and their variability. The results suggest that the two examined cerebral diseases do affect driving performance, and there are common driving patterns for both cerebral diseases, as well as particular characteristics of specific pathologies. More specifically, drivers with these cerebral diseases drive at lower speeds and with larger headway compared to healthy drivers. Moreover, they appear to have difficulties in positioning the vehicle on the lane. Cerebral diseases also appear to significantly affect reaction times at incidents.

**Key-words:** driving performance; driving simulator; Mild Cognitive Impairment; Alzheimer's disease

## 1 BACKGROUND

2  
3 The task of driving requires the ability to receive sensory information, process the information,  
4 and to make proper, timely judgments and responses (1, 2). Various motor, visual, cognitive  
5 and perceptual deficits can affect the ability to drive. These deficits are either age-related or  
6 caused by neurologic disorders and lead to reduced driver fitness and increased crash risk.  
7 More specifically, diseases affecting a person's brain functioning (e.g. presence of specific  
8 brain pathology due to neurological diseases as Alzheimer's disease) may significantly impair  
9 the person's driving ability (3, 4, 5, 6). These conditions have obvious impacts on driving  
10 performance, but in mild cases and importantly in the early stages, they may be imperceptible  
11 in one's daily routine yet still impact one's driving ability. Furthermore, neuropsychological  
12 parameters associated with driving performance are reaction time, visual attention, speed of  
13 perception and processing, and general cognitive and executive functions. These parameters  
14 show considerable decline with age or at the presence of cognitive impairments and are  
15 associated with the probability of accident involvement (7).

16 Relatively little is known about the competence of drivers with Mild Cognitive  
17 Impairment (MCI). This constitutes a considerable gap, given that MCI is a pathological  
18 condition with high prevalence in the general population as ~15% of people >65 years old are  
19 affected. In addition, MCI eventually develops into dementia with a high annual rate (8). The  
20 concept of MCI has been described as a cognitive state that lies between normal aging and  
21 dementia (9). Persons with MCI exhibit cognitive decline beyond what is expected to be normal  
22 for age, but are otherwise functioning well and do not meet criteria for dementia. Research  
23 results are not conclusive on the extent to which MCI is affecting driving behaviour and safety.  
24 MCI drivers seem to have statistically significant driving behaviour deviation (maintaining  
25 speed, wheel stability, and lateral control) from the control driving population (10). Another  
26 study tried to ascertain which cognitive features contribute to the safe driving behaviour of  
27 MCI drivers. Participants drove using a driving simulator and seemed to have considerable  
28 difficulties in maintaining lateral control on a road and in following the vehicle ahead (11).

29 Moreover, Alzheimer's disease (AD) is the most frequent form of dementia worldwide  
30 (12). In the early stages of the disease, a variety of symptoms can be observed with gradually  
31 progressive memory impairment being the most prominent symptom. Additional deficits may  
32 be present, including, visuospatial deficits, impaired attention, executive dysfunction and  
33 judgment, verbal fluency and confrontation naming (13). Another research showed that AD  
34 drivers (especially the elderly) made many more safety errors (the most common errors were  
35 lane violations) (14). Longitudinal evidence was provided for a decline in driving performance  
36 over time, primarily in early-stage dementia of the Alzheimer type (15). Mild AD significantly  
37 impaired simulated driving fitness, while MCI limitedly affected driving performance (16).  
38 What is more, an accurate judgment of someone's own ability to drive and the resultant  
39 compensatory behaviour are prerequisites of safe driving, an ability that is often impaired in  
40 dementia (17).

41 Given that the percentage of the elderly in society is increasing (18), and that the level  
42 of motorization also increases (19), the investigation of the impact of these conditions on driver  
43 performance becomes quite critical. It is also highlighted that relatively few studies exist  
44 analyzing the effect of a specific pathology on driving performance, and even fewer studies  
45 comparing different pathologies.

## 48 **OBJECTIVES**

49

50 The objective of this research is to analyze the driving performance of drivers with Alzheimer's  
51 disease (AD) and Mild Cognitive Impairment (MCI), by means of a driving simulator  
52 experiment. Various driving performance measures are examined in both rural and urban  
53 environment, e.g. mean speed, lateral position, steering angle, headway, reaction time at  
54 unexpected events etc. The driving performance of drivers impaired by the above pathologies  
55 is compared to that of healthy controls by means of Repeated Measures General Linear  
56 Modeling techniques.

57 The research questions that are examined in this paper are: how MCI and AD affect  
58 various measures of driving performance and how these diseases interact with road and traffic  
59 parameters.

60 The paper starts a presentation of a large driving simulator experiment, in which the  
61 driving performance of the impaired and healthy drivers was examined in different driving  
62 scenarios, following a thorough neurological and neuropsychological assessment of all  
63 participants. The existing sample size and characteristics are presented next, followed by a  
64 short description of the analysis methods, dependent and independent variables. The results are  
65 presented and discussed, and some concluding remarks are provided.

66

## 67 **DRIVING SIMULATOR EXPERIMENT**

68

### 69 **Overview**

70

71 This research is based on a methodological framework for the combined assessment of traffic,  
72 behavioural, medical, neurological and neuropsychological parameters on driving  
73 performance. In this framework, the aspects of driver behaviour and safety research addressed  
74 are inherently interdisciplinary, and an experiment was designed by an interdisciplinary  
75 research team including:

- 76 • **Transportation Engineers** - Department of Transportation Planning and Engineering,  
77 of the National Technical University of Athens (NTUA)
- 78 • **Neurologists** - 2nd Department of Neurology, University of Athens Medical School, at  
79 ATTIKON University General Hospital, Haidari, Athens
- 80 • **Neuropsychologists** - Department of Psychology, University of Athens, the 2nd  
81 Department of Neurology of ATTIKON University General Hospital, Haidari, Athens  
82 and the Aristotle University of Thessaloniki.

83 According to the objectives of the analysis, the experiment includes three types of  
84 assessment:

- 85 • **Medical / neurological assessment:** The first assessment concerns the administration  
86 of a full clinical medical, ophthalmological and neurological evaluation, in order to well  
87 document the characteristics of each of these disorders (e.g. MCI, AD, PD,  
88 Cerebrovascular disease (stroke) as well as other related parameters of potential impact  
89 on driving (e.g. use of medication affecting the Central Nervous System).
- 90 • **Neuropsychological assessment:** The second assessment concerns the administration  
91 of a series of neuropsychological tests and psychological-behavioural questionnaires to  
92 the participants. The tests carried out cover a large spectrum of Cognitive Functions:  
93 visuospatial and verbal episodic and working memory, general selective and divided  
94 attention, reaction time, processing speed, psychomotor speed etc.
- 95 • **Driving at the simulator:** The third assessment concerns the driving behaviour by  
96 means of programming of a set of driving tasks into a driving simulator for different  
97 driving scenarios.

98 The first and second assessments are carried out at the ATTIKON University General  
99 Hospital, and their description is beyond the scope of this paper; for details the reader is referred  
100 to Papadimitriou et al. (2014) (20). The third assessment, (driving simulator experiment) takes  
101 place in the NTUA Road Safety Observatory and is presented in detail in the following section.  
102

### 103 **Driving at the simulator**

104

105 The NTUA driving simulator is a motion base quarter-cab manufactured by the FOERST  
106 Company. The simulator consists of 3 LCD wide screens 40'' (full HD: 1920x1080pixels),  
107 driving position and support motion base. The dimensions at a full development are  
108 230x180cm, while the base width is 78cm and the total field of view is 170 degrees. It's worth  
109 mentioning that the simulator is validated against a real world environment (21).

110 The design of the driving scenarios includes driving in different road and traffic  
111 conditions, such as in a rural, urban area with high and low traffic volume, with or without  
112 external distraction. More specifically, the driving simulator experiment begins with one  
113 practice drive (usually 10-15 minutes), until the participant fully familiarizes with the  
114 simulation environment. Afterwards, the participant drives two sessions (approximately 20  
115 minutes each). Each session corresponds to a different road environment: a rural route that is  
116 2.1 km long, single carriageway and the lane width is 3m, with zero gradient and mild  
117 horizontal curves and an urban route that is 1.7km long, at its bigger part dual carriageway,  
118 separated by guardrails and the lane width is 3.5m. Two traffic controlled junctions, one stop-  
119 controlled junction and one roundabout are placed along the route.

120 Within each road / area type, two traffic scenarios and three distraction conditions are  
121 examined in a full factorial within-subject design. The traffic conditions examined include:

- 122 • Low traffic conditions - ambient vehicles' arrivals are drawn from a Gamma  
123 distribution with mean  $m=12\text{sec}$ , and variance  $\sigma^2=6\text{ sec}$ , corresponding to an average  
124 traffic volume  $Q=300\text{ vehicles/hour}$ .
- 125 • High traffic conditions - ambient vehicles' arrivals are drawn from a Gamma  
126 distribution with mean  $m=6\text{sec}$ , and variance  $\sigma^2=3\text{ sec}$ , corresponding to an average  
127 traffic volume of  $Q=600\text{ vehicles/hour}$ .

128 The distraction conditions examined concern undistracted driving, driving while  
129 conversing with a passenger and driving while conversing with a mobile phone.

130 Consequently, in total, each session (urban or rural) includes six trials of the simulated  
131 route. During each trial, 2 unexpected incidents are scheduled to occur at fixed points along  
132 the drive. More specifically, incidents in rural area concern the sudden appearance of an animal  
133 (deer or donkey) on the roadway, and incidents in urban areas concern the sudden appearance  
134 of an adult pedestrian or of a child chasing a ball on the roadway or of a car suddenly getting  
135 out of a parking position and getting in the road. The hazard does appear at the same location  
136 for the same trial (i.e. rural area, high traffic) but not at the same location between the trials, in  
137 order not to have learning effects. Regarding the time that the hazard appears, it depends on  
138 the speed and the time to collision in order to have identical conditions for the participant to  
139 react, either they drive fast or slowly. Thus, there is no possibility for the incident to appear  
140 closely or more suddenly to a participant than to another.

141 The experiment is counterbalanced concerning the number and the order of the trials.  
142 However, rural drives were always first and urban drives were always second. This was decided  
143 for the following reasons: It was observed that urban area causes more often simulation  
144 sickness to the participants and thus it was decided to have the urban scenario second and  
145 secondly, counterbalancing in driving area means that we would have twice as much driving  
146 combinations which leads to much larger sample size requirements.

147 Finally, impaired participants are to carry out the simulator experiment while under  
 148 their usual medication, so that their driving performance corresponds to their everyday  
 149 condition, as treated by their neurologist.

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151 **ANALYSIS METHODS AND DATA**

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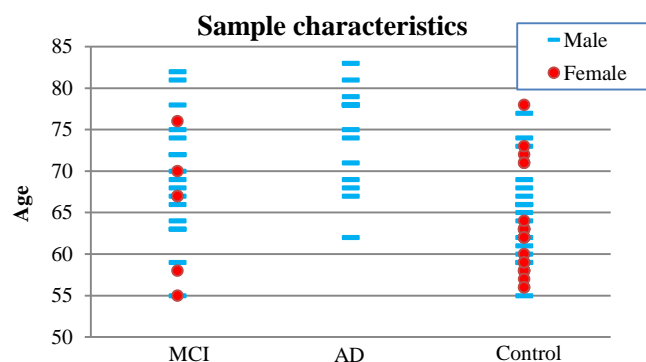
153 The aim of this research is to analyze and compare the driving performance of MCI, AD and  
 154 healthy drivers in rural and urban road environment. For that purpose, four trials of the  
 155 simulator experiment are selected: the undistracted driving trials in rural area and the  
 156 undistracted driving trials in urban area in both low and high traffic volumes.

157 The analysis method selected is the Repeated Measures General Linear Model (GLM).  
 158 The repeated measures GLM is the equivalent of the one-way ANOVA, but for related, not  
 159 independent groups. A repeated measures GLM may be based on a within-subjects or a mixed  
 160 design (22).

161 At the present time more than 140 participants have participated in the driving simulator  
 162 experiment in approximately 15 months time. However, about 30 participants had simulator  
 163 sickness issues (a usual phenomenon in driving simulators) and didn't complete the driving  
 164 trials of the experiment. For that reason they are eliminated from the study. Moreover there are  
 165 35 participants of younger age (<55 years old) who are eliminated too for age representativity  
 166 reasons. The analysis is thus based on the existing related sample of the (ongoing) simulator  
 167 experiment of healthy and impaired participants of over than 55 years of age who completed  
 168 all of the examined four trials were selected, which consists of **75 participants** (49 males).  
 169 More specifically, the sample of the present study consists of:

- 170 • 38 healthy “controls” (66.4 years old on average),
- 171 • 14 AD patients (74.6 years old on average) and
- 172 • 23 MCI patients (68.3 years old on average).

173 It is noted that the gender distribution of healthy and impaired drivers is currently not  
 174 fully similar, i.e. the proportion of females is lower in the impaired drivers group (no female  
 175 AD participant), which is in any case representative of the general population. On the other  
 176 hand, the age distributions of impaired and healthy drivers are comparable to a satisfactory  
 177 degree, taking into account that it is expected that impaired drivers are on average older than  
 178 healthy ones (see Figure 1).



179

180 **FIGURE 1 Age distribution of the sample, health condition and gender distribution**

181

182 The variables examined in the present research include a between-subject variable,  
 183 namely the presence of a disease (AD or MCI). They also include one within-subject variables,  
 184 namely the traffic scenario (low or high traffic volume). It is noted that area type (rural, urban)  
 185 is not examined as a within-subject variable, because all participants drove first in rural area  
 186 and then in urban area; this was done for practical reasons but obviously results in order effects,  
 187 and consequently the two area types are examined separately and not comparatively. The

188 driving performance measures examined include both longitudinal control measures and lateral  
 189 control measures. More specifically:

- 190 • Longitudinal control measures:
- 191 ○ **Mean speed** (mean speed of the driver along the route, excluding the small
  - 192 sections in which incidents occurred, and excluding junction areas)
  - 193 ○ **Headway** (time distance between the front of the simulator vehicle and the front
  - 194 of the vehicle ahead)
  - 195 ○ **Reaction time at unexpected incidents** (time between the first appearance of the
  - 196 event on the road and the moment the driver starts to brake in milliseconds)
- 197 • Lateral control measures:
- 198 ○ **Lateral position** (vehicle distance from the central road axis in meters),
  - 199 ○ **Lateral position variability** (the standard deviation of lateral position),
  - 200 ○ **Mean wheel steering angle** (in degrees)
  - 201 ○ **Steering angle variability** (the standard deviation of steering angle).

202 **RESULTS**

203 A Repeated Measures General Linear Model was developed for each one of the driving  
 204 performance measures considered. The analysis of variance for the within subject variables  
 205 (Table 1) indicated that traffic volume has a significant effect on mean speed, mean headway  
 206 and lateral position in both road environments, and lateral position variability and steering  
 207 angle variability only on rural road. Regarding the between-subject variable, the presence of a  
 208 disease was found to significantly affect mean speed and reaction time in both road  
 209 environments. The presence of a cerebral disease seems to affect mean headway, lateral  
 210 position variability and steering angle variability only in rural roads and lateral position only  
 211 in urban road environment.  
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 214

215 **TABLE 1 Tests of within and between subjects in rural and urban road environment**

216

	Rural Road				Urban Road			
	Tests of <b>Within-Subjects Contrasts</b> (Source <b>Traffic</b> )		Tests of <b>Between-Subjects Effects</b> (Source <b>Disease</b> )		Tests of <b>Within-Subjects Contrasts</b> (Source <b>Traffic</b> )		Tests of <b>Between-Subjects Effects</b> (Source <b>Disease</b> )	
	<b>F</b>	<b>p-value</b>	<b>F</b>	<b>p-value</b>	<b>F</b>	<b>p-value</b>	<b>F</b>	<b>p-value</b>
<b>Mean speed</b> (km/h)	17,292	,000**	24,634	,000**	20,327	,000**	6,000	,004**
<b>Mean headway</b> (sec)	69,665	,000**	14,218	,000**	9,569	,003**	,294	,746
<b>Reaction time</b> (millisec)	1,785	,186	2,828	,066*	,466	,498	2,656	,078 *
<b>Lateral position</b> (m)	106,116	,000**	,375	,689	5,690	,021**	2,552	,085 *
<b>Lateral position variability</b> (st.dev of lateral position)	29,125	,000**	4,840	,011**	,430	,515	1,374	,262
<b>Steering angle</b> (degrees)	1,368	,246	,358	,701	,051	,823	,381	,685
<b>Steering angle variability</b> (st.dev of steering angle)	9,586	,003**	3,435	,038**	,037	,849	,313	,732

217 \* significant at 90%, \*\* significant at 95%

218 **Effect of cerebral diseases in rural roads**

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The results of the GLMs fitted to the data for the various longitudinal and lateral control measures of the rural driving session, in terms of parameter estimates and their statistical significance, are presented in Tables 2 and 3. Table 2 refers to the longitudinal control measures in rural area, whereas table 3 refers to lateral control measures in rural area.

Cerebral diseases appear to have a significant effect on driver mean speed in rural driving environment. AD and MCI patients drive at significantly lower mean speed compared to healthy drivers, both at low and high traffic volumes. AD drivers' speed is significantly lower than the MCI drivers' speed, in both driving environments.

Moreover, cerebral diseases appear to have a significant effect on mean headway in rural roads but only for AD patients: they have significantly longer mean headway compared to healthy drivers at both traffic environments. This is happening for MCI drivers too, but the confidence level was only 85%. AD drivers have much longer mean headway compared with the MCI drivers. These results are intuitive, given that lower speeds naturally result in larger headways, with a given distribution of ambient traffic on the road network. It is also noted that headways at low traffic volumes are longer for all driver groups, which is also intuitive.

Significant differences in the driving behavior of healthy and impaired drivers were also identified as regards the drivers' reaction time at unexpected incidents in rural roads (sudden appearance of a deer or a donkey). In both traffic environments impaired drivers have about 0.5 sec longer reaction times than the healthy ones. This difference was found to be statistically significant at 90% confidence level for both impaired groups and both traffic volumes, except for MCI drivers in high traffic volume who have longer reaction times than the control group statistically significant at 95% confidence level.

**TABLE 2 Parameter estimates of the repeated measures GLM - Longitudinal control measures for rural driving environment**

Parameter Estimates		Low Traffic Volume				High Traffic Volume			
Dependent Variable		B	Std. Error	t	Sig.	B	Std. Error	t	Sig.
Mean speed (km/h)	Intercept	47,907	1,207	39,699	,000 **	45,296	,993	45,595	,000 **
	MCI	-6,112	1,965	-3,110	,003 **	-6,235	1,618	-3,854	,000 **
	AD	-13,982	2,326	-6,012	,000 **	-13,383	1,915	-6,990	,000 **
	Control	0				0			
Mean headway (sec)	Intercept	46,634	4,759	9,799	,000 **	22,382	4,730	4,732	,000 **
	MCI	12,361	7,750	1,595	,115	12,035	7,703	1,562	,123
	AD	40,432	9,172	4,408	,000 **	51,314	9,116	5,629	,000 **
	Control	0				0			
Reaction time (millisec)	Intercept	923,048	153,950	5,996	,000 **	996,250	159,113	6,261	,000 **
	MCI	481,918	250,715	1,922	,059 *	532,628	259,123	2,056	,043 **
	AD	580,278	296,700	1,956	,054 *	446,428	266,688	1,674	,097 *
	Control	0				0			

\* significant at 90%, \*\* significant at 95%

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Regarding lateral position in rural area, it is worth mentioning that the width of the driving lane is 3m (i.e. very narrow), so the drivers don't have so much flexibility in positioning

251 their vehicle on the lane. Thus, there are no significant differences in lateral position for the  
 252 drivers. Positive values indicate driving more closely to the right border of the road.

253 On the other hand, the lateral position variability seems to have differences for MCI  
 254 drivers in both traffic volumes. Lateral position variability is lower than that of healthy  
 255 controls, and this may be a result of the lower speed and their more conservative driving.

256 Finally, no statistically significant differences are observed in mean steering angle in  
 257 rural area, between control group and impaired drivers - a positive mean steering angle means  
 258 more counter-clockwise steering movements, which is in accordance with a lateral position  
 259 closer to the central road axis. On the other hand, there is statistically significant variability in  
 260 steering angle; all examined impaired drivers in high traffic volume environment have lower  
 261 steering angle variability.

263 **TABLE 3 Parameter estimates of the repeated measures GLM - Lateral control measures**  
 264 **for rural driving environment**  
 265

Parameter Estimates		Low Traffic Volume				High Traffic Volume			
Dependent variable		B	Std. Error	t	Sig.	B	Std. Error	t	Sig.
Lateral position (m)	Intercept	1,491	,024	61,979	,000 **	1,605	,022	72,596	,000 **
	MCI	,029	,039	,746	,458	,030	,036	,830	,410
	AD	,010	,046	,224	,823	,014	,043	,328	,744
	Control	0				0			
Lateral position variability (st.dev of lateral position)	Intercept	,299	,009	31,520	,000 **	,266	,009	29,164	,000 **
	MCI	-,036	,015	-2,330	,023 **	-,027	,015	-1,821	,073 *
	AD	,024	,018	1,310	,194	,017	,018	,994	,324
	Control	0				0			
Steering angle (degrees)	Intercept	-1,793	,082	-21,993	,000 **	-1,949	,090	-21,680	,000 **
	MCI	-,102	,133	-,770	,444	,230	,146	1,571	,121
	AD	,045	,157	,284	,777	-,131	,173	-,757	,452
	Control	0				0			
Steering angle variability (st.dev of steering angle)	Intercept	17,747	,307	57,739	,000 **	17,646	,260	67,984	,000 **
	MCI	-,756	,501	-1,511	,135	-1,088	,423	-2,573	,012 **
	AD	-,505	,592	-,853	,397	-1,558	,500	-3,114	,003 **
	Control	0				0			

266 \* significant at 90%, \*\* significant at 95%

267  
 268 **Effect of cerebral diseases on urban roads**  
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270 The results of the GLMs fitted to the data for the various longitudinal and lateral control  
 271 measures of the urban driving session, in terms of parameter estimates and their statistical  
 272 significance, are presented in Tables 4 and 5. Table 4 refers to the longitudinal control measures  
 273 in urban area, whereas table 5 refers to lateral control measures in urban area.

274 In urban road environment similar statistical results with the rural area type were  
 275 observed, regarding the longitudinal control measures. Mean speed is significantly lower for  
 276 impaired drivers in urban driving environment. AD and MCI drivers seem to drive at the same  
 277 speed in both at low and high traffic volumes.

278 However, cerebral diseases appear not to have a significant effect on mean headway in  
 279 urban roads. Only MCI patients seem to have significantly longer mean headway compared to  
 280 healthy drivers only at high traffic environment.

281 Finally, regarding the reaction times, they appear to be improved for the impaired  
 282 drivers compared to the rural road. They are more closely to the reaction times of the control  
 283 group and have significant differences at 90% confidence level only in low traffic volume. This  
 284 is possibly also due to the learning effect resulting from the fact that the urban area trials took  
 285 place after the rural area trials for all participants

286

287 **TABLE 4 Parameter estimates of the repeated measures GLM - Longitudinal control**  
 288 **measures for urban driving environment**

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Parameter Estimates		Low Traffic Volume				High Traffic Volume			
Dependent variable			Std. Error	t	Sig.	B	Std. Error	t	Sig.
Mean speed (km/h)	Intercept	33,677	,899	37,454	,000 **	30,372	,692	43,870	,000 **
	MCI	-4,854	1,733	-2,801	,007 **	-3,713	1,334	-2,783	,007 **
	AD	-4,357	2,435	-1,789	,079 *	-4,636	1,875	-2,473	,017 **
	Control	0				0			
Mean headway (sec)	Intercept	48,628	5,149	9,444	,000 **	23,784	2,309	10,302	,000 **
	MCI	7,538	9,944	,748	,461	11,989	4,449	2,695	,009 **
	AD	4,340	13,944	,311	,757	7,266	6,252	1,162	,250
	Control	0				0			
Reaction time (millisec)	Intercept	1294,487	66,621	19,431	,000 **	1284,224	62,967	20,395	,000 **
	MCI	198,056	115,973	1,708	,092 *	139,062	121,353	1,146	,257
	AD	296,187	165,711	1,787	,078 *	209,693	170,515	1,230	,224
	Control	0				0			

290 \* significant at 90%, \*\* significant at 95%

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292 Regarding lateral position in urban area, MCI patients appear to drive at longer distance  
 293 from the central road axis compared to healthy drivers, both at high and at low traffic volumes  
 294 (statistically significant at 90% confidence level). AD drivers in high traffic volume have  
 295 significant differences in lateral position too. This is observed only in urban road environment  
 296 and it's worth mentioning, that the width of the driving lane is 3,5m, there are 2 lanes in the  
 297 bigger part of the route, so there are opportunities for overtaking and there are choices in  
 298 positioning the vehicle on the road. It seems that in urban areas the high traffic volume makes  
 299 the conditions more complex for the impaired drivers and leads them to drive more closely to  
 300 the right border of the road. Especially for AD drivers there is significant increase in the  
 301 variability of the lateral position in high traffic volume (in contrast with all other cases).

302 Statistically significant differences are not observed for mean steering angle, or for the  
 303 variability in the steering angle between control group and impaired drivers.

304

305 **TABLE 5 Parameter estimates of the repeated measures GLM – Lateral control**  
 306 **measures for urban driving environment**

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Parameter Estimates	Low Traffic Volume	High Traffic Volume
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Dependent Variable		B	Std. Error	t	Sig.	B	Std. Error	t	Sig.
<b>Lateral position (m)</b>	Intercept	2,961	,103	28,864	,000 **	3,064	,103	29,690	,000 **
	MCI	,305	,184	1,756	,099 *	,326	,185	1,762	,083 *
	AD	,171	,278	,616	,541	,514	,279	1,839	,071 *
	Control	0				0			
<b>Lateral position variability (st.dev of lateral position)</b>	Intercept	1,560	,098	15,839	,000 **	1,522	,099	15,351	,000 **
	MCI	,210	,190	1,107	,273	,195	,191	1,021	,312
	AD	,171	,267	,640	,525	,482	,268	1,797	,078 *
	Control	0				0			
<b>Steering angle (degrees)</b>	Intercept	6,967	,203	34,374	,000 **	7,336	,294	24,963	,000 **
	MCI	,136	,391	,348	,729	-,379	,566	-,670	,506
	AD	,546	,549	,996	,324	,196	,796	,246	,807
	Control	0				0			
<b>Steering angle variability (st.dev of steering angle)</b>	Intercept	22,872	,753	30,365	,000 **	22,463	1,328	16,918	,000 **
	MCI	,368	1,452	,254	,801	1,646	2,559	,643	,523
	AD	-,821	2,040	-,402	,689	,102	3,596	,028	,978
	Control	0				0			

\* significant at 90%, \*\* significant at 95%

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## DISCUSSION

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This paper analyzed the driving performance of drivers with cerebral diseases, with focus on the comparative assessment of AD and MCI pathologies. Relatively few studies exist analyzing the effect of a specific pathology on driving performance, and even fewer studies comparing different pathologies. The majority of these studies indicate serious deterioration in driving performance of drivers with a cerebral disease compared to healthy drivers.

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The research questions examined in this paper are: how the examined pathologies affect various measures of driving performance and how they interact with road and traffic parameters. For this purpose, four trials were selected from a large driving simulator experiment including twelve trials in total, namely those concerning undistracted driving in rural and urban areas with low or high traffic volume. These four trials were based on a mixed (within- and between-subject) counterbalanced design. Both longitudinal and lateral control measures are examined, e.g. speed, lateral position, steering angle, headway, reaction time at unexpected events etc. by means of Repeated Measures General Linear Modeling techniques. This research in progress is one of the few which attempt to compare different pathologies in terms of their effect on driving performance.

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Summarizing the results, AD and MCI drivers were found to drive at significantly lower speeds compared to the healthy control group drivers, both at low and at high traffic volume. AD drivers in rural environment have even lower mean speed compared to the MCI drivers, but in urban roads their speed is approximately the same. As would be expected, this reduced speed results under given ambient traffic conditions in increased headways, both at low and at high traffic volumes in rural roads, however in urban environment there are statistically significant differences in mean headways only for MCI drivers in high traffic volume.

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Analyzing the reaction times of the impaired drivers at unexpected incidents, it is observed that MCI and AD drivers have significantly longer reaction times in rural road in both traffic volumes compared with the control group. In urban area, they have longer reaction

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337 times, but only in low traffic volume this difference is significant. Compared with each other,  
338 MCI drivers seem to have slightly better reaction times than the AD group in most cases. These  
339 longer reaction times of impaired drivers are likely to be confirmed by their neurological and  
340 neuropsychological assessments (at the present time the medical and neuropsychological  
341 database is under preparation in order to be finalized and used in future statistical analyses, and  
342 thus it is not available).

343 Analyzing the lateral control measures it is observed that in rural area there are more  
344 statistically significant differences between the driving groups except for lateral position  
345 because of the very narrow lane in rural area. More specifically, MCI patients drive more  
346 closely to the right border of the road in urban area and in both traffic volumes, whereas AD  
347 drivers only in high traffic volume in urban area. Regarding the variability of this measure, a  
348 significantly higher variability is highlighted for AD drivers in high traffic volume in urban  
349 area. It seems that the more complex is the driving environment the more the AD drivers have  
350 difficulty in maintaining the position of the vehicle on the lane. Finally, in rural area both  
351 impaired groups have low steering variability in high traffic volume that is a result of their low  
352 speed and conservative driving.

353 The effect of the sample representativity is something that needs to be highlighted; the  
354 age and gender distributions of the impaired and control populations seem balanced at the  
355 present time, however sample representativity should be improved in the next steps of the  
356 ongoing experiment. The larger proportion of female drivers in the control group is  
357 representative, as the proportion of female AD or MCI patients is low in the general population.  
358 On the other hand, the average age of the examined groups should be totally balanced, in order  
359 to eliminate the possibility that the differences of the driving behaviour between the examined  
360 groups are a result of age distribution.

361 Finally, the results are to be considered within the limiting context of driving simulator  
362 studies - driving performance is known to be more accurately and reliably estimated by means  
363 of on-road studies. However, the relative effects of impaired vs healthy drivers are known to  
364 be quite identifiable in simulator studies.

365

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367

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