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The impact of cognitive disorders and other risk factors on reaction time of drivers: a Structural Equation Model approach

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Abstract

Cognitive function consists a cornerstone for driving performance, irrespective of age. The objective of the current research is the analysis of traffic and safety behaviour of drivers with neurological diseases affecting cognitive functions. Towards that aim, the impact of cognitive disorders and other risk factors on reaction time of drivers was investigated. A driving simulator experiment was carried out and a large dataset of 225 drivers was analyzed. A Structural Equation Model (SEM) in the field of assessing driving behaviour of drivers with cerebral diseases was developed. Results indicated that the group of patients had a longer reaction time in all examined conditions compared to the cognitively intact group. A combination of the most robust cognitive and non-cognitive risk factors may allow an accurate prediction of driving behaviour and prospective accident risk.

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Keywords: Driving simulator; Reaction time; Older drivers; Cognitive disorders; Structural Equation Modelling technique.

1. Introduction

Decline in cognitive abilities and functions can be an important contributor to the driving problems encountered by older adults. A neuropsychological assessment may provide a practical approach in order to evaluate this aspect of driving safety risk (Anderson et al., 2012). In particular, the neurological disorders affecting cognitive functions concern diseases with high prevalence in the general population: Mild Cognitive Impairment (MCI), Alzheimer's disease (AD) and Parkinson's disease (PD).

This research is an inter-disciplinary effort entering the scientific fields of traffic and safety behaviour of drivers on one hand and neurological disease affecting cognitive functions on the other. The objective of this research is the

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analysis of traffic and safety behaviour of drivers with cognitive disorders through a driving simulator experiment. More specifically, the study aims to capture the interaction of certain brain pathologies, other related parameters (i.e. demographic, medical, and neuropsychological) and driver distraction with respect to reaction time. The combined effect of these key parameters on reaction time might provide useful insight on driver traffic and safety behaviour analysis. Given the interaction of several scientific areas in research of impaired driving due to cognitive disorders (transportation engineering, neurology and neuropsychology), this study covers a field of research with an obvious and unique interdisciplinary nature, which has not been examined in the past.

The rest of the paper is organised as follows: first, the existing literature and its main findings are synthesized. Then, an overview of the data collected for the analysis is presented. Subsequently, a brief description of the methodological approach is provided. In the next chapter, the significant findings are drawn and the results of the statistical analysis performed are summarized. Lastly, conclusions are highlighted and the limitations along with some proposals for further research are clearly stated.

2. Background

To date, several studies have been conducted in order to identify the perceptual, behavioral, or cognitive impairments that may lead to unsafe driving in a given patient group (Pavlou et al., 2016). Nevertheless, relatively little attention has been directed toward the broader issue of relationship between neuropsychological performance and road safety, across a broad spectrum of age-related conditions. It should be mentioned that the evaluation of cognitive abilities can provide valuable information regarding driving road safety and crash risk, across diagnostic categories (Yannis et al., 2013).

A literature review was carried out examining in a comprehensive way driving behaviour and road safety, ways to assess driving performance indicators, driving simulator characteristics as well as neurological diseases affecting cognitive functions (MCI, AD or PD) and how these cerebral diseases affect driving performance (Pavlou et al., 2015).

2.1 Mild Cognitive Impairment (MCI)

Reviewing studies about patients with MCI, it seems that although they experience subtle changes in their driving competence are still able to drive. However, a level of impairment compared to healthy controls is generally being reported meaning that they still constitute a population at risk that warrants close supervision. Unsafe MCI drivers were more likely to make errors in speed control and they also faced difficulties at roundabouts, intersections, straight driving and parking (Eramudugolla et al., 2021). Moreover, MCI patients faced difficulties associated with late detection combined with increased reaction time and slowed response to relevant targets in the peripheral field of view as well as difficulties associated with divided attention between tasks requiring switching from automatic to conscious processing particularly of long duration (Vardaki et al., 2019).

2.2 Alzheimer's disease (AD)

Reviewing studies about patients with AD, driving performance declines considerably in individuals with AD and several on-road and simulator studies indicated worse driving performance for AD group compared to healthy controls in several driving measures. An interesting study was conducted (Frittelli et al., 2009) and results demonstrated that patients with mild AD performed significantly worse than MCI subjects and controls on time to collision, reaction time, length of trip and number of off-road events. In another research (Uc et al., 2006), participants with AD had difficulty responding to driving conditions that pose a hazard for a rear-end collision.

2.3 Parkinson's disease (PD)

Reviewing studies about patients with PD, it seems that their driving capacity is mainly compromised due to cognitive deficits. Moreover, pronounced difficulties in several driving indexes seem to appear in drivers with PD under demanding driving conditions that involve increased cognitive load reaction time. Stolwyk et al. (2006) found that participants with PD were disproportionately affected on operational level driving behavior compared to healthy group. It was also revealed that patients with PD sacrificed concurrent task performance in order to maintain their driving performance. Similarly, an on-road driving experiment was conducted and results indicated that the PD group had a longer failure rate, indicating more on-road errors (Classen et al., 2011).

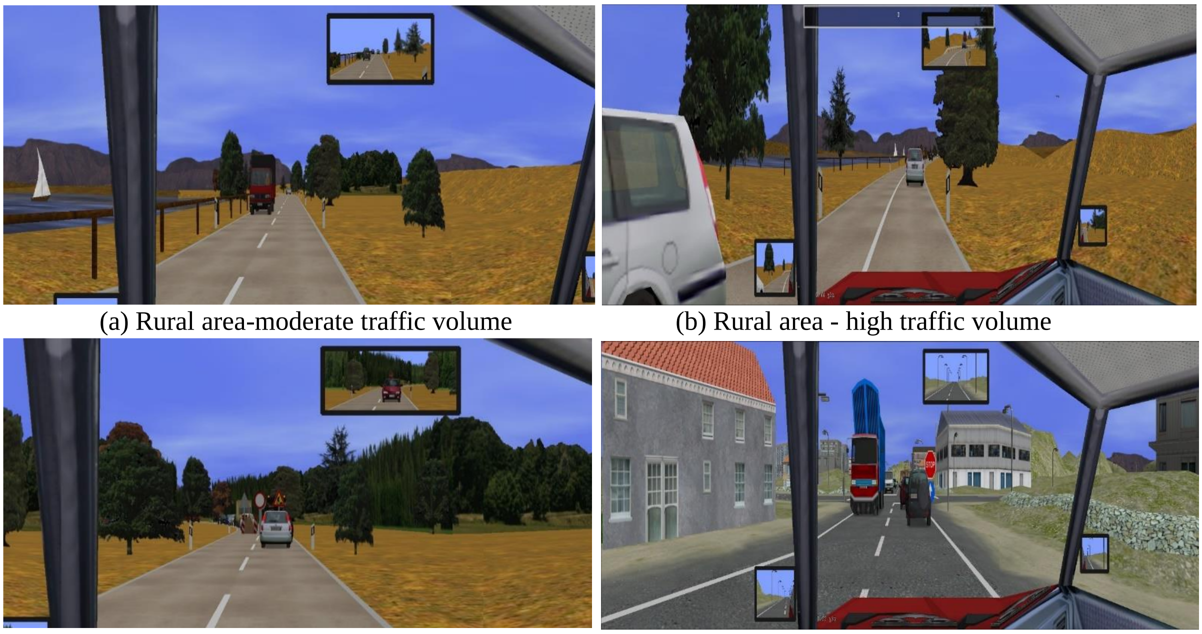
3. Data collection

For the purpose of this research, a large-scale driving simulator experiment was carried out, comprising a medical/neurological and neuropsychological assessment of 225 active drivers (76% males - 24% females): 133 "patients" with a cerebral disease (28 AD patients, 45 MCI patients, 25 PD patients and 35 patients with other neurological disorders affecting cognition) and 92 "Controls" without any cognitive disorder, and a set of driving tasks for different scenarios. The driving simulator experiment took place at the special room of the Laboratory of Traffic Engineering of the Department of Transportation Planning and Engineering of the School of the National Technical University of Athens (NTUA).

The design of the driving scenarios included driving in different road, traffic and distraction conditions, such as in a rural and urban area, with high and low traffic volume, while conversing through a mobile phone, or while conversing with a passenger, or under no distraction. During each trial, two unexpected incidents were scheduled to occur at fixed points along the drive. More specifically, incidents in rural area concerned the sudden appearance of an animal on the roadway, and incidents in urban areas concerned the sudden appearance of a child chasing a ball on the roadway, or of a vehicle suddenly getting out of a parking position and getting in the road.

After completing the driving simulator tasks, participants were asked to fill in a questionnaire concerned their driving habits and their driving behaviour. The questionnaire was divided in different sections: driving experience - car use, self - assessment of the older driver, distraction-related driving habits, emotions and behaviour of the driver, anger expression inventory during driving, and history of accidents, near misses and traffic violations.

Figure 1 illustrates the different traffic scenarios under different road environment, traffic volumes and distraction conditions which were examined in a full factorial within-subject design.



(a) Rural area-moderate traffic volume (b) Rural area - high traffic volume

(c) End of rural trial (d) Urban area high traffic volume

Fig. 1. Overview of the different traffic scenarios under different road environment, traffic volumes and distraction conditions

It is worth mentioning that this research was approved by the Ethics Committee of the University General Hospital "ATTIKON". Thus, informed consent was obtained from all individuals studied. In addition, it was explained to them that participation was on a voluntary basis and they were able to withdraw any time they wished to. All drivers were informed on the duration of their engagement, the nature of the study, as well as the type of information that they would be asked to provide. Lastly, participants were ensured of the confidentiality and anonymity of the procedure.

Figure 2 depicts the boxplots of reaction time in rural areas with different traffic volumes (high and low) and different distraction conditions (no distraction, conversation with passenger, mobile phone use while driving). It was observed that controls have the best reaction times overall in rural area, whereas AD and PD groups have the worst reaction times (more than 40% worse reaction times than the control group). Then, the mobile phone use has an important effect on reaction time for AD and PD groups. Finally, conversing with passenger didn't seem to have a significant effect on reaction time in all examined groups.

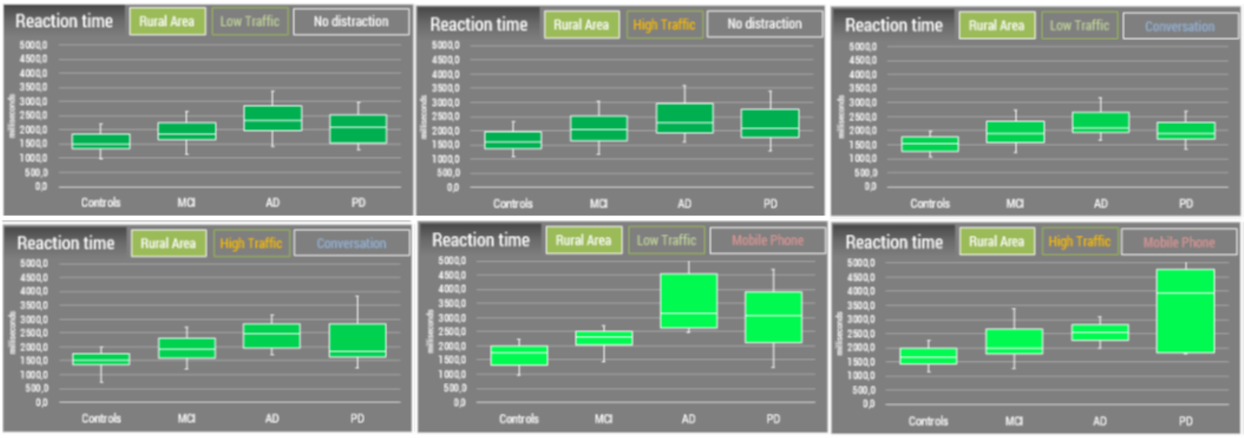


Fig. 2. Boxplots of reaction time in rural area with different traffic volumes and distraction conditions

4. Methodological overview

In this section, a brief overview covering the mathematical background is provided. More specifically, the statistical analysis methodology developed and implemented was based on Structural Equation Models (SEMs). It should be highlighted that SEM belongs to the model family of latent variable analysis. For instance, it refers to a multivariate technique which can support multiple-input and multiple-output modelling. In the context of the present study, SEM provides an appropriate approach to quantify the impact of neurological diseases affecting cognitive functions, distraction, age and road and traffic environment on the observed variable "reaction time". Additionally, the quantified impact of two latent variables regarding neurological state and neuropsychological state of the drivers on the observed variable "reaction time" is analyzed.

Several studies have utilized SEM techniques in order to model complex interrelationships typically involving unobserved concepts expressed as latent variables, with application in road safety and traffic engineering domains as well. As per the aforementioned, SEM have been applied to model psychological factors (Satiennam et al., 2018), unsafe driving (Scott-Parker et al., 2013) or perception of risk and driving tasks on road safety attitudes of drivers (Ram & Chand, 2016). Using matrix notation, SEM can be expressed by certain fundamental equations, as follows:

The structural equation model is specified as:

$$\eta = B\eta + \Gamma\xi + \zeta \qquad (1)$$

where: η is a vector expressing the latent dependent (unobserved) variables; ξ is a vector expressing the latent independent (exogenous) variables; ζ is a vector expressing the regression error term in η; B is a matrix expressing the regression coefficients of η in the SEM relationship; Γ is a matrix expressing the regression coefficients of ξ in the SEM relationship.

The measurement model for y is specified as:

$$y = \Lambda_y\eta + \varepsilon \qquad (2)$$

where: y is a vector expressing the dependent (response) variables, Λ_y is a vector expressing the regression coefficients for the dependent variables y on η; ε is a vector expressing the regression error term in y

The measurement model for x is specified as:

$$x = \Lambda_x \xi + \delta \quad (3)$$

where: x is a vector expressing the independent (predictor) variables; Λ_x is a vector expressing the regression coefficients for the independent variables x on ξ; δ is a vector expressing the regression error term in x

5. Results

In the SEM applied, the impact of various observed and latent variables on reaction time was explored. More specifically, the core objective is the quantification of the impact of neurological diseases affecting cognitive functions, age, distraction, road and traffic environment, neurological state and neuropsychological state on the observed variable "reaction time". Figure 3 provides the SEM structure regarding the reaction time.

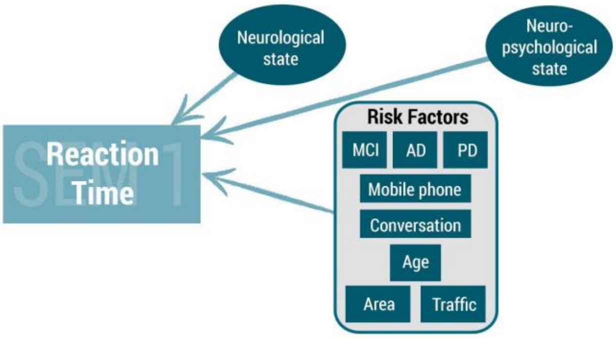


Fig.3. Structure of reaction time SEM

It should be noted that the traffic flow was not found to significantly affect the dependent variable and thus, this variable was eliminated from the final SEM. The estimation results are presented in Table 1, while Table 2 provides and overview of the summary statistics.

Table 1. Estimation results of the reaction time SEM

Latent variables	**Est.**	**Std.err**	**Z-value**	**P(>|z|)**
Neuropsychological State (latent 1)				
Witkin's Embedded Figure Test	1.000			
Brief Visuospatial Memory Test	1.962	0.048	40.927	<.001
Comprehensive Trail Making Test (1)	-6.752	0.405	-16.685	<.001
Hopkins Verbal Learning Test (RI)	0.415	0.020	20.818	<.001
Neurological State (latent 2)				
Tandem Walking: Errors	1.000			
Tandem Walking: Completion Time	5.557	0.873	6.364	<.001
Patient Health Questionnaire (PHQ-9)	9.956	2.416	4.120	<.001
Foot taping errors	0.829	0.170	4.885	<.001
Regressions	**Est.**	**Std.err**	**Z-value**	**P(>|z|)**
Reaction time				
Disease - MCI	103.575	52.205	1.984	.047
Disease - AD	327.075	87.927	3.492	<.001
Disease - PD	381.056	88.544	4.304	<.001
Urban Area	-345.309	33.260	-10.382	<.001
Advanced Age	190.137	43.877	4.333	<.001
Distraction - Conversation	80.614	37.769	2.134	0.033
Distraction - Mobile Phone	225.921	54.088	4.177	<.001
Neuropsychological State *(latent)*	-20.899	6.464	-3.233	<.001
Neurological State *(latent)*	-789.943	226.670	-3.485	<.001

Table 2. Summary statistics of the reaction time SEM

Summary statistics	**ML**
Minimum Function Test Statistic	1928.87
Degrees of freedom	81
Goodness of fit	
SRMR	0.138
RMSEA	0.132
CFI	0.722
TLI	0.702

A critical finding that supports the validity of the overall SEM is that the contribution of the observed variables on the construction of the latent variables (both neuropsychological state and neurological state) was in all cases statistically significant. In addition, regarding the regression analysis, all predictors had a significant contribution on the prediction of the reaction time. Finally, the obtained goodness-of-fit measures were generally close to the respective limits.

In the model applied, reaction time was the dependent observed variable while the independent variables included a diagnosis of a cerebral disorder (i.e. AD, PD or MCI), neurological state, neuropsychological state, driver distraction, drivers' age and area type. With respect to the effect of cerebral disorders on reaction time, it was revealed that the presence of MCI, AD or PD had a significant negative impact on reaction time. Concerning the effect of age, young and middle-aged drivers were found to outperformed older drivers in term of reaction time.

Furthermore, neuropsychological state and neurological state that are commonly impaired in patients with cerebral disorders had a significant unique contribution on predicting better reaction times. Regarding the effect of in-vehicle distraction, both distractors had a statistically significant negative effect on reaction time. Finally, with respect to the area and traffic characteristics, results demonstrated that area type was a critical factor affecting drivers' reaction time as in urban areas reaction time was significantly affected in a positive way. On the other hand, traffic conditions didn't appear to influence reaction time significantly.

The respective path diagram of the SEM is presented in Figure 4. Blue lines express a significant impact on better reaction time, red lines express a significant impact on worse reaction time, while grey lines express the absence of a statistically significant association (grey lines correspond to variables that are not included in the model). Furthermore, dashed lines indicate which variables create the latent ones, while continuous lines indicate which variables exist in the regression part of the SEM. Lastly, the label values represent the parameter estimates.

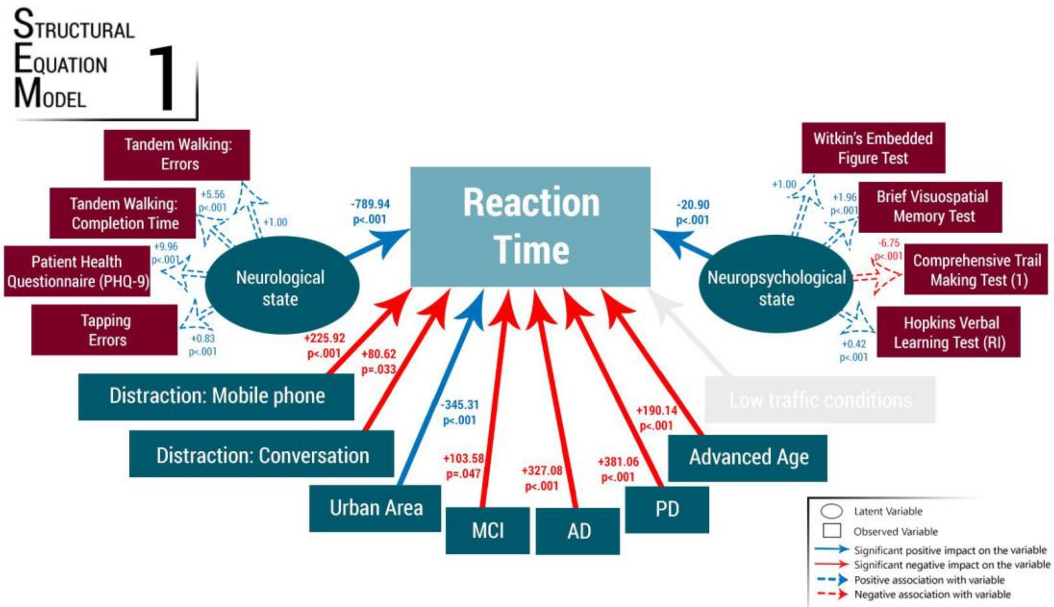


Fig. 4. Path diagram of the SEM model for reaction time

6. Discussion

Analyzing the reaction time of the patients at unexpected incidents, it was observed that participants with neurological diseases affecting cognitive functions had significantly longer reaction times compared to the control group. In comparison with each other, drivers with MCI seemed to have slightly better reaction times than the groups of AD and PD in most cases. Interestingly, in rural area, 70% of the patients with neurological diseases affecting cognitive functions had reaction times larger than 2 seconds. At the same time, no patient was below the lower limit of the “typical area”, whereas 42% of participants with AD or PD were above the upper limit of the “typical area” in both rural and urban driving environments.

Taking into account the neurological diseases affecting cognitive functions, drivers with MCI, AD or PD were associated with significantly worse reaction time as compared with cognitively intact individuals of similar demographics. In addition, the latent variable “neurological state” had a significant positive effect on reaction time. The aforementioned results are in agreement with literature findings which have proven that persons with amnestic MCI and patients with AD found to have longer reaction time tasks with increasing complexity compared to cognitively healthy elderly (Gorus et al., 2008).

Regarding driver distraction, conversation with the passenger had a worse reaction time, while mobile phone use had a significant negative effect on reaction time. This finding is consistent with what other studies have found (Choudhary & Velaga, 2017). The negative effect of mobile phone on driving behaviour can be probably explained by the accumulating role of two synergistic mechanisms. Firstly, due to the amount of physical and cognitive resources that drivers allocate for performing the distraction task. Secondly, by adopting a compensatory behaviour that however only partially counterbalances the impact of distraction on overall driving behaviour (Papantoniou et al., 2017).

With respect to age, it was revealed that advanced age had a significant negative impact on reaction time. The role of advanced age on driving behaviour appeared to generalize as well on the control group of this study that included cognitively intact individuals. This was probably due to the fact that as aging is the major risk factor for dementia or other crucial diseases, older adults tend to have a worse driving performance with longer reaction times as compared to youngers (Ribeiro & Castelo-Branco, 2019).

As far as area and traffic characteristics are concerned, urban area had a significant positive impact on reaction time. This conclusion is in line with international literature and it can be interpreted by the fact that the complex environment of the urban region increased the levels of awareness and led to better a reaction time (Basak et al., 2013). Lastly, low traffic conditions hadn’t any significant impact on reaction time, which was an intuitive finding. In high traffic, the complicated road environment, including a lot of interactions between vehicles, had an overall negative effect on reaction time.

However, there are some limitations and restrictions that should be mentioned. More specifically, the influence of weather conditions was not taken into consideration in the present study. Based on the evidence that drivers react differently under different circumstances with respect to weather and traffic conditions, it is of great interest to investigate reaction time using weather, traffic and driver data.

The investigation of other significant factors could be also included in future research, such as drug abuse, alcohol consumption or the use of seat belt. Additionally, demographic characteristics such as gender, educational level, or driving experience could be also taken into account. As per further research directions, the experimental sample size could be strengthened in terms of size (i.e. more participants with MCI, AD and PD), as well as in terms of location and origin (i.e. MCI, AD and PD drivers in Greece may present differences in driving behaviour with drivers of the same brain pathologies living in other countries). In the future, different types of the neurological diseases affecting cognitive functions, such as dementia, stroke or multiple sclerosis could be inserted in the research.

7. Conclusions

This study aimed to analyze the traffic and safety behaviour of drivers with neurological diseases affecting cognitive functions. To achieve this object, the impact of cognitive disorders and other risk factors on reaction time of drivers was investigated. A driving simulator experiment was carried out and a large dataset of 225 drivers was analyzed. Within the framework of latent analysis, a Structural Equation Model (SEM) was implemented aiming to investigate the impact of common cerebral diseases (i.e. AD, PD and MCI) on reaction time. Also, through this analysis, the role of additional potential predictors of driving behaviour was explored. Results indicated that regarding the effect of cerebral disorders on reaction time, the impact of cognitive disorders was significantly detrimental on the observed variable “reaction time”. The AD group of drivers had the worse driving behaviour profile among the examined groups with neurological diseases affecting cognitive functions.

The analysis of the neurological diseases affecting cognitive functions and other age-related and neuropsychological characteristics in combination with the driving performance of the general population is a very crucial domain and a scientific challenge. Overall, the results of this research can potentially contribute to a significant reduction of road crashes and fatalities especially for the elderly, if the data and the results be exploited by the authorities in order to implement appropriate road safety policy directions regarding the vulnerable group of elderly drivers. Enhanced understanding of the medical, behavioural and social issues related to impaired driving due to neurological diseases affecting cognitive functions will lead to more appropriate driver training, criteria for driver license renewal for persons belonging to vulnerable groups, more appropriate legislation and awareness campaigns.

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