National Technical University of Athens
School of Civil Engineering
Department of Transportation Planning and Engineering

Traffic and safety behaviour of drivers with neurological diseases affecting cognitive functions

A Doctoral Thesis by

Dimosthenis I. Pavlou

Submitted in partial fulfilment of the requirements for the award of Doctor of Philosophy

Advisory board:
G. Yannis, Professor, NTUA
J. Golias, Professor, NTUA
S.G. Papageorgiou, Associate Professor, NKUA

Athens, September 2016

Summary

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 the present inter-disciplinary PhD thesis is **the analysis of traffic and safety behaviour of drivers with neurological diseases affecting cognitive functions**. More specifically, the impact of certain brain pathologies on driving performance, driving errors, reaction time and accident probability is under investigation. The driving behaviour is examined in terms of both traffic and safety behaviour and the neurological diseases affecting cognitive functions concern diseases with high prevalence in the general population: Alzheimer's disease (AD), Parkinson's disease (PD), and Mild Cognitive Impairment (MCI). The central objective of this PhD dissertation was addressed by:

» designing and implementing **a large driving simulator experiment**,
» developing an **original methodology** for the assessment of the impact of drivers' neurological diseases affecting cognitive functions on their driving performance taking also into account their neuropsychological and demographic characteristics as well as the main road safety and traffic characteristics,
» quantifying **the impact of neurological diseases affecting cognitive functions** directly on driving performance, driving errors, reaction time and accident probability,
» **comparing the driving performance** of drivers with different neurological diseases,
» examining **the impact of driver distraction** on the performance of drivers with cerebral diseases.

The PhD thesis aims to capture the interaction of neurological diseases affecting cognitive functions, other related parameters (i.e. demographic, medical, and neuropsychological) as well as road and traffic conditions, and driver distraction with respect to driving behaviour. The **combined effect of these key parameters** on driving performance, driving errors, reaction time and accident probability 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 neurological diseases affecting cognitive functions (transportation engineering, neurology and neuropsychology), this PhD thesis covers a field of research with an **obvious and unique interdisciplinary nature**, which has not been examined in the past. The analysis of the neurological diseases affecting cognitive functions and other demographic and neuropsychological characteristics in combination with the driving performance of the general population, is a very crucial domain and a scientific challenge at the same time. In order to achieve the objectives of this PhD dissertation, four discrete methodological steps were

followed: 1st) Extensive **literature review**, 2nd) **Methodological approach**, 3rd) Design and implementation of a **large driving simulator experiment**, and 4th) Development and application of an innovative **statistical analysis**.

Firstly, **an exhaustive literature review was carried out** examining in a comprehensive way driving behaviour and road safety, ways to assess driving behaviour, driving simulator characteristics as well as neurological diseases affecting cognitive functions (MCI, AD and PD) and how these cerebral diseases affect driving performance. Reviewing studies about patients with MCI, of those studies assessing driving performance through on road testing, it seems that MCI patients, 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. 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. Reviewing studies about patients with PD, several lines of previous research indicate that driving capacity in patients with PD 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.

Moving on, an **innovative statistical analysis methodology** in the field of assessing driving behaviour of drivers with cerebral diseases was developed. This innovative methodological approach is based on literature review regarding simulator experiment, neurological and neuropsychological design principles, driving performance, cognitive and neurological state measures and statistical analysis methods. Methodological review indicated that **latent model analysis and especially structural equation models have never been implemented** in the field of driver behaviour of patients with neurological diseases affecting cognitive functions. For that reason and within the framework of this PhD dissertation, an innovative statistical analysis methodology has been developed, and consists of five steps: a) Descriptive Analysis, b) Analysis Of Variance (ANOVA), c) Regression Models (Generalized Linear Models), d) Principal Component Analysis (PCA), and e) Structural Equation Models (SEMs).

Moving on, based on the literature and methodology review, **a large driving simulator experiment was carried out** at the Department of Transportation Planning and Engineering of the NTUA, aiming to assess driving performance of patients with

neurological diseases affecting cognitive functions. The experiment was designed in an **inter-disciplinary way** and included three scientific branches:

» **Driving at the simulator**: The first assessment concerns a set of driving tasks into a driving simulator for different driving scenarios: two different driving areas (rural/urban), two different traffic volumes (moderate/high), three distraction conditions (undistracted driving, driving while conversing with a passenger, and while conversing on a hand-held mobile phone), while unexpected incidents happened in front of them (sudden appearance of an animal or of a child chasing a ball or of a car suddenly getting out of a parking position).

» **Medical / neurological assessment**: The second assessment concerns the administration of a full clinical medical, ophthalmological and neurological evaluation, in order to well document the characteristics of each of the examined disorders (MCI, AD, PD).

» **Neuropsychological assessment**: The third assessment concerns the administration of a series of neuropsychological tests and psychological-behavioural questionnaires to the participants. The tests carried out cover a large spectrum of Cognitive Functions: visuospatial and verbal episodic and working memory, general selective and divided attention, reaction time, processing speed, psychomotor speed.

The sampling scheme included 225 participants (76% males - 24% females):

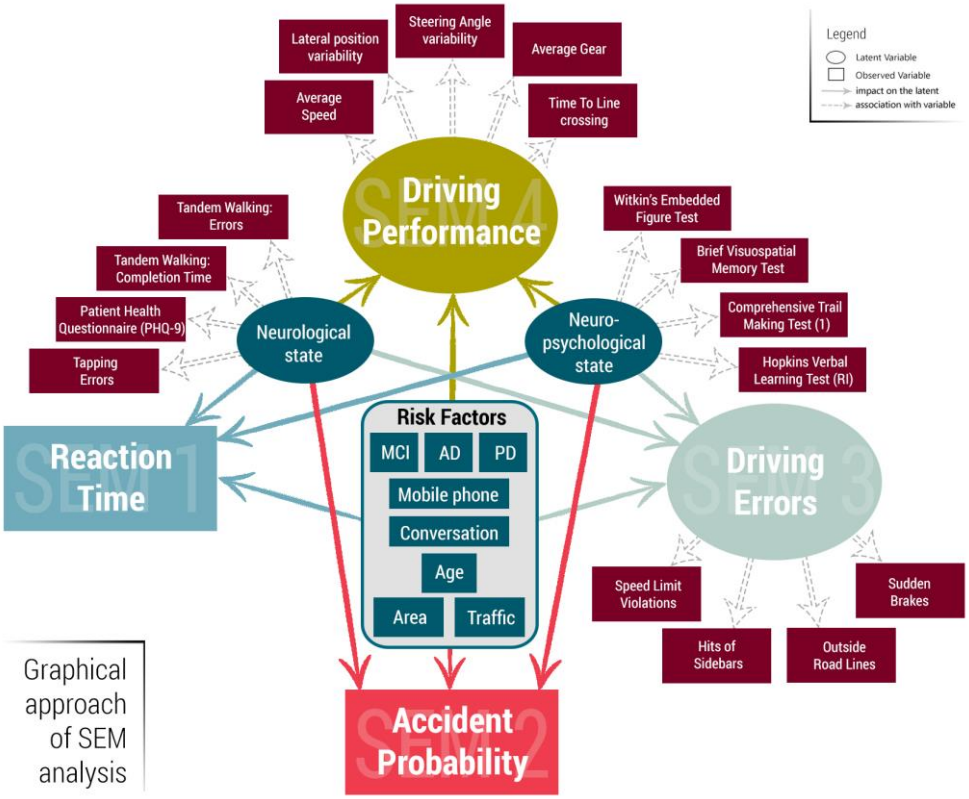
» **133 "patients"** with a neurological disease affecting cognitive functions (28 AD, 45 MCI, 25 PD patients, and 35 patients with other cognitive disorders)

» **92 "Controls"** without any cognitive disorder

Then, **six discrete Driving Simulator Data Processing Levels (PL)** were developed, in order to suitably deal with the large and diversified amount of data collected and to conclude to an "All Drivers and All Assessments Processed Data File" which was analyzed by means of **a dedicated and innovative statistical analysis method**. In the first step, the **descriptive analysis** correlated mean speed, time headway, lateral position, steering angle variability, reaction time at unexpected incidents, accident probability, and driving errors, with traffic volume, driving area, regarding age and cerebral disease of the participants. Then, **two Analysis Of Variance (ANOVA)** were extracted regarding identification of significant differences in the driving performance indexes extracted from the driving simulator assessment and in the answers extracted from the behaviour questionnaire, between two groups: groups of healthy controls and patients with neurological diseases affecting cognitive functions. In the third step, within the framework of the explanatory analysis, the development of **a series of Regression**

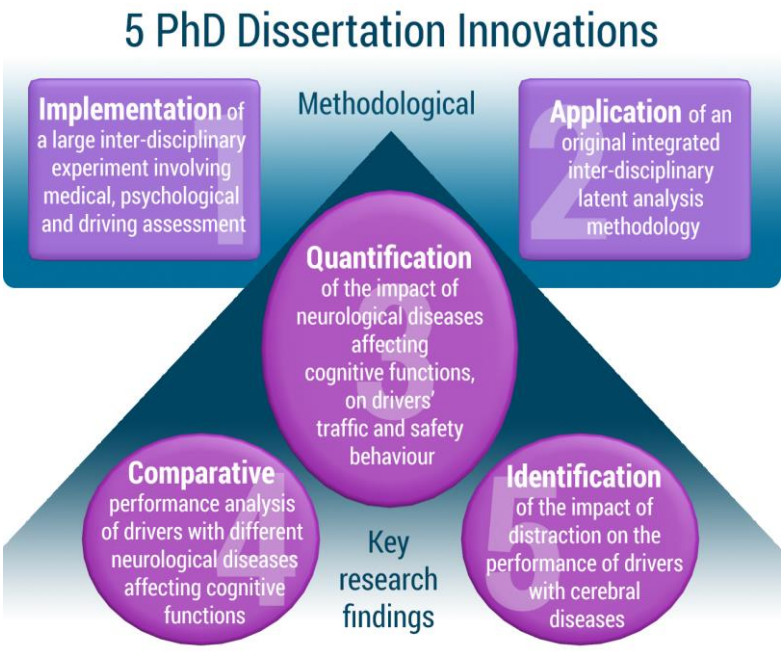
Models took place regarding key performance parameters in order to estimate the effect of cerebral diseases and driving characteristics on specific driving performance parameters and indirectly on driving behaviour and road safety.

In the fourth step, **four Principal Component Analyses (PCA)** were implemented regarding driving performance, driving errors, neuropsychological state and neurological state, in order to investigate which observed variables are most highly correlated with the common factors and how many common factors are needed to give an adequate description of the data. In the fifth and final step, the core statistical analysis of the present PhD thesis took place, including the implementation of **four Structural Equation Models (SEMs)** for the first time in the scientific field of driving behaviour of drivers with neurological diseases affecting cognitive functions. Within the framework of latent analysis and based on the factor loadings that were extracted from the PCA analyses, **four latent variables were developed** namely, "driving performance", "driving errors", "neurological state" and "neuropsychological state" in order to implement four SEMs. The four SEMs were developed aiming to quantify the impact of MCI, AD and PD, driver distraction, driver characteristics, "neurological state", "neuropsychological state" as well as road and traffic environment directly on the observed variables "reaction time" and "accident probability" and on the latent variables "driving performance" and "driving errors".



In the **first and the second SEMs**, the objective is the quantification of the impact of neurological diseases affecting cognitive functions, distraction, age and road and traffic environment on the observed variables "**reaction time**" and "**accident probability**". Additionally, the quantified impact of two latent variables regarding neurological state and neuropsychological state of the drivers on the observed variables is analyzed. In the **third and fourth SEMs**, the key latent variables reflects the underlying "**driving errors**" and "**driving performance**" and the objective is the quantification of the impact of neurological disease affecting cognitive functions, distraction, driver characteristics and road and traffic environment on "driving errors" and "driving performance". Additionally, the quantified impact of latent variable regarding "neurological state" and latent variable regarding "neuropsychological state" of the drivers on the latent variables "driving errors" and "driving performance" is analyzed.

The synthesis of the key research findings that were extracted within the framework of this PhD dissertation lead to several conclusions of great significance with five innovative scientific contribution points.



The first innovation of this PhD dissertation is methodological. **The design and implementation of a large scale inter-disciplinary experiment** which includes two scientific branches, a traffic engineering, and a medical (neurological and neuropsychological), is a central component of the present PhD thesis. Because of the integration of these different scientific disciplines involved in impaired driving research (**traffic engineering, neurology and neuropsychology**), this PhD dissertation covers a research field with an obvious but not previously exploited multidisciplinary nature.

The second innovation of this PhD dissertation is also methodological, suggesting the implementation of **four latent variables covering all three fields of this inter-disciplinary PhD thesis**: "driving performance" and "driving errors" extracted from the

driving simulator experiment, "neurological state" extracted from the neurological database and "neuropsychological state" extracted from the neuropsychological database, in order to **construct four Structural Equation Models (SEMs)**. The four latent variables were developed using the most critical indexes (neurological, neuropsychological, and driving measures) extracted from the PCA analyses.

Latent analysis allowed an important scientific step forward from piecemeal analyses to a sound combined analysis of the **inter-disciplinary interrelationship** between risk factors, neurological state, neuropsychological state, driving performance, driving error and accident probability at unexpected incidents. **It is the first time and it is also considered a methodological originality of this PhD dissertation**, that latent variables reflecting neurological and neuropsychological status (neurological state and neuropsychological state) interact with other latent driving variables (driving performance an driving errors) and with other observed driving variables such as reaction time and accident probability.

The third innovation is the quantification of the impact of neurological diseases affecting cognitive functions, on drivers' traffic and safety behaviour, which is considered to be the core of this PhD dissertation, regarding the key research findings. The first three statistical steps, indicated **statistically significant differences between the group of patients with neurological diseases affecting cognitive functions and the healthy controls** of similar demographics in several driving performance measures. Patients were found to drive at significantly lower mean speed and had larger time headway compared to the healthy drivers. Analyzing the lateral control measures it was observed that patients with MCI drove more closely to the right border of the road (slightly yet significantly). It was observed that patients had significantly larger reaction times in all examined conditions compared with the cognitively intact group. Moving on to the accident probability, significantly higher accident probability was detected for the AD group in all examined conditions and for the MCI and PD groups only in urban area. Finally, the ANOVA investigated the self-stated questionnaires and indicated that drivers with MCI, AD and PD **are aware of their deterioration of their driving performance**.

Moving on to the SEM analysis, it was indicated that **drivers with MCI, AD and PD overall performed significantly worse than the healthy controls regarding the four examined driver behaviour characteristics**. More precisely, they were associated with significantly lower levels of the latent variable "driving performance" that reflected a broad range of driving indexes and were associated with significantly worse "reaction

time". Also, the clinical conditions of AD and PD were associated with a negative impact on accident probability. Finally, none of the clinical groups showed a significantly increased amount of driving errors. Latent variable **"neuropsychological state"** had a positive effect on all outcome variables. Latent variable **"neurological state"** had a significant positive effect on "driving performance", "driving errors" and reaction time, whereas, its impact on accident risk was not statistically significant.

Moving on to the impact of other risk factors on driver behaviour, **conversation with the passenger** was not found to have a critical impact on driving performance, driving errors and accident probability, indicating that drivers don't alter their driving behaviour in an important way under this type of distraction, but they have worse reaction time. On the other hand, **mobile phone use** had a significant negative effect on "driving performance", "accident probability" and "reaction time" but not on "driving errors". **Advanced age** had a significant negative impact on "driving performance", "driving errors" and reaction time, whereas, its impact on accident risk was not statistically significant. **Urban area** had a significant negative impact on "driving performance", whereas its impact on "driving errors", reaction time and accident probability was positive. **Low traffic conditions** affected positively the "driving performance", whereas it hadn't any significant impact on "driving errors", reaction time and accident probability. Nonetheless, **the parameter that renders originality to this analysis** is the development of latent variables for the evaluation of driving behaviour that encompasses a variety of indexes. In addition, another novel element is the application of multivariate SEM models that make the exploration of the **unique impact** of neurological diseases affecting cognitive functions feasible on driving behaviour.

The fourth innovation of this PhD dissertation is derived also from the key research findings and concerns the comparative performance analysis of drivers with different neurological diseases affecting cognitive functions. The results indicated **AD as the riskiest group of drivers** (had the greatest impact on accident probability and driving performance and almost the greatest on reaction time), **followed by PD**, whereas the group of MCI is considered as safer compared to the other two examined brain pathologies.

Finally, the fifth innovation of this PhD dissertation concerns the effect of distraction the performance of drivers with MCI, AD and PD, by exploring driving while conversing with a co-passenger and driving while conversing through a handheld mobile phone. Exploring and quantifying the impact of distraction on drivers with MCI, AD and PD has

not been addressed so far among the international scientific community. It appeared that overall, the distraction conditions didn't have such a significant impact on driving performance measures in the group of controls, in contrast with the findings extracted from the **patients' groups regression analyses in which the impact of distraction and especially the mobile phone use, was detrimental**. In particular, the **reaction time** of drivers with brain pathologies **increased more than 30%** under the driving condition with the use of **mobile phone**, whereas in the group of cognitively intact drivers the equivalent increase was about 10%. Moreover, the group of drivers with neurological diseases affecting cognitive functions had a striking increase of the risk of being engaged in a car accident when using a mobile phone. Also, the presence of a **conversation with a passenger had an impact** on the driving performance of the patients, but of **a smaller magnitude** as compared to the case of the mobile phone use.

The results of this PhD dissertation **can be exploited in the development of recommendations and measures** for addressing all aspects of impaired driving due to neurological diseases affecting cognitive functions. The application of this methodology revealed also a number of open issues for further research in the inter-disciplinary field of driving behaviour and brain pathologies (i.e. **periodically assess** the driving behaviour of patients with cerebral diseases over time). It is important to mention that **every driver with a neurological disease affecting cognitive functions should be treated individually, through a modern interdisciplinary driving evaluation** including medical, neurological and neuropsychological criteria for safe driving and of course assessment of driving performance through simulator tasks or on-road trials. Additionally, it should be in positive direction an effective monitoring of drivers that are at-risk for developing an underlying neurological condition that is associated with unsafe driving and the development of interventions that have the capacity to improve or preserve the driving fitness of older individuals and of drivers with cerebral diseases.

Overall, the results of this PhD thesis can potentially contribute to a significant reduction of road accidents and fatalities, 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 drivers with neurological diseases affecting cognitive functions. 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 and licensing, criteria for driver license renewal for persons belonging to vulnerable groups, more appropriate legislation and awareness campaigns.