博士論文

Detection of Variations in the Neuromuscular State of a Driver via Mechanical Arm Admittance and Its Application to Haptic Steering Guidance

(腕の力学的アドミッタンスによるドライバの神経筋状態の変化の検知と力覚操舵支援への適用)

ジョリ　アントナ
Joly Antonin

I would like to thank my dear Kana-chan, without whom, I would not have been able to complete this program. Furthermore, I would also like to warmly thank my parents, sisters and friends for their support.
Moreover, I would like to express my gratitude to my supervisor, Professor Nakano Kimihiko, whose expertise, understanding, and patience, added considerably to my graduate experience.
Finally, I would like to thank Professor Kaneko Shigehiko, Professor Suda Yoshihiro, Professor Itoh Makoto, and Professor Shino Motoki of which their advices helped me to improve the content of my thesis.

Abstract

The originality of this work lies in the detection of impaired neuromuscular condition using driving-related variables, and the consideration of the neuromuscular condition of the driver when investigating the impact of application of haptic steering guidance on the neuromuscular condition of the driver. The computation and understanding of the neuromuscular condition of the driver is critical since a misinterpretation can lead to substantial difference in the assistance that is needed to improve the condition of the driver. In the literature, studies that focus on haptic guidance investigates its effect on external metrics that result from neuromuscular condition, such as driving performances, reaction time, lane keeping, but do not investigate the neuromuscular condition itself. In this dissertation, the detection of an impaired neuromuscular condition, which is critical for the safety of the driver, is made possible using driving-related variables. This action is addressed by acquiring the neuromuscular condition of the driver and conclude on its variations. This computation is made regarding to the reliability of the results, so that the estimation of the neuromuscular condition of the driver can be trusted to take a decision on the need of assistance. Moreover, it is demonstrated in this dissertation that the neuromuscular condition of the driver can be improved using short term haptic steering guidance application, which should pay special attention to the yaw rate variations of the vehicle in complex driving situations.

While driving, the main interaction of the driver with the control of the trajectory and the speed are made through the steering wheel and the gas or brake pedals. Thus, within the frame of driving control, the condition of the driver influences the accuracy of the actions of the drivers that aim to control the trajectory and the speed of the vehicle. The condition of the driver is related to the human neuromuscular condition, which refers to the unconscious response of the muscle to a perturbation regarding the stability of the dynamical joint. Playing the role of the regulator of the condition of the driver, the human neuromuscular system is a complex system of interactions that connects different physiological mechanisms, such as muscle activation, muscle co-contraction, body coordination, joint stabilization, body posture and balance. The movements of each limb of the human body are controlled by this system. Because of neuromuscular fatigue, which can be caused by several factors, the control of the vehicle can be impacted negatively, and the safety of the driver can be compromised. The cause of a fatigued neuromuscular condition can be natural, when the body is exhausted after a long period without rest, for example, or irregular, when the driver is under the influence of alcohol, for example. For both natural and irregular influences, the reaction of the driver to unexpected event, such as obstacle apparition on the road, is largely shifted in time, or does not even happen. In most cases, this modification in the driver steering performance, gas pedal performance or brake performance leads to vehicle accidents. In order to remedy this issue, the neuromuscular condition of the driver must be monitored in real-time to detect any variations that may indicate a deprived condition and assist the driver in consequence.

Detecting the variations of the condition of the driver using driving-related variables such as the steering wheel angle or torque would benefit the ergonomics of the assistance system. Thus, it was demonstrated in previous studies that mechanical arm admittance permits to investigate the condition of the driver with the computation in the frequency domain of equations that include driving-related terms, or the computation in the frequency domain of equations that include bio-mechanical terms. This metric has been used in previous studies to estimate the condition of the

driver in real-time car application and demonstrates the ability to assess accurately the variations of the condition of the driver. It is used in this dissertation to estimate the neuromuscular condition of the driver and its variations.

For investigating the impact of the variation of the condition of the driver on mechanical arm admittance, drivers presenting a deprived neuromuscular condition are asked to perform driving simulations, in which the estimation of mechanical arm admittance is performed. The amplitude of mechanical arm admittance of these trials is compared with trials performed with the same participants and in the same driving scenarios, at the exception that the participants presented a normal neuromuscular condition. This method permits to establish the influence of deprived conditions on mechanical arm admittance and quantify their effects. In this dissertation, the tested deprived conditions are drowsiness and distraction. It is demonstrated that these deprived conditions are increasing the amplitudes of mechanical arm admittance on different frequency ranges, which expresses a decrease of the arm stiffness and decreased capacities to react to steering perturbations. The occurrence of these decreases in amplitude of mechanical arm admittance occurred on different frequency ranges that varies depending on the type of impairment. Indeed, for a drowsy condition, which suggests both physical and mental impairment, the frequency range of mechanical arm admittance affected covers a larger frequency bandwidth compared to distraction, for which the impairment is only mental.

To remedy the negative impact of impaired neuromuscular condition, the application of haptic steering feedbacks on the steering wheel is proposed. Haptic steering guidance control applied to the steering wheel is a technology that provides steering feedbacks, which their amplitudes depends on geometric considerations of the trajectory of the vehicle compared with a desired trajectory. Usually, the amplitude of steering feedbacks is higher as the vehicle shift further from the desired trajectory. The geometric considerations of haptic steering guidance model are: the lateral position and velocity of the vehicle regarding the desired trajectory, and the yaw angle and rate difference regarding the yaw angle and rate of the desired trajectory. With haptic steering guidance control, drivers remain in the driving loop decision, and are constantly encouraged to perform accurate steering operations in order to maintain accurate lane-keeping performances.

To investigate the effect of haptic steering guidance control on the condition of the driver, the influence of the application of haptic steering guidance control on mechanical arm admittance is investigated. It is reviewed that the amplitude of mechanical arm admittance can be decreased by the application of haptic steering guidance, revealing an increase of the stiffness of the arm and an increased capacity to resist to steering perturbations. This statement denotes that the application of haptic steering feedbacks can influence the condition of the driver, enhancing the resistance to steering perturbations.

Moreover, optimal designs of haptic steering feedbacks, aiming at maximizing the decrease in amplitude of mechanical arm admittance, are investigated. It is found that haptic steering guidance design that focuses on the monitoring of the yaw rate of the vehicle, while maintaining a normal level of monitoring of the other variables, can optimize the decrease in amplitude of mechanical arm admittance. In this situation, the condition of drivers is influenced optimally, and the driving performances are improved.

Furthermore, it is reviewed that the benefits of application of haptic steering feedbacks to the steering wheel is restricted to specific conditions since drivers tend to present overreliance on the assistance while driving in complex driving situations. Whereas, they also present improved driving performances in term of lane-keeping and steering stability. Consequently, it is acceptable to apply haptic steering feedbacks for short periods of time in complex driving situations. In simple driving situations, haptic steering feedbacks dos not influence the condition of the driver because of the easiness of the steering tasks. As a result, the application of haptic steering guidance for short period of time seems beneficial to influence the condition of the driver who presents an impaired neuromuscular condition, aiming at improving the driver condition and driving performances.

To sum up the content of this dissertation, a driver can be influenced positively using short term steering haptic steering feedbacks, which pay a special attention to the monitoring of the yaw rate of the vehicle, in complex driving situations. Else, the haptic steering guidance does not have effect on the condition of the driver or can even induce overreliance on the assistance system. Additionally, an impaired condition can be detected by observing increase patterns, depending on the frequency, of the amplitude of mechanical arm admittance that relate to a modification of the neuromuscular condition of the driver. Furthermore, the detection of impaired condition and the improvement of the neuromuscular condition of the driver can be made in real-time, which can fit real applications. The advantage of the proposed method in this dissertation is that the detection of an impaired condition can be done via the analysis of physical reaction of the driver. It enhances the quality of the estimation of the neuromuscular condition of the driver and can provide a double validation of the estimation of the condition of the driver if coupled with another system, e.g. a camera that detects variation of facial features of a driver.

Nomenclature

ADAS	-	Advanced Driving Assistance System
IVIS	-	In-Vehicle Information Systems
MAA	-	Mechanical arm admittance
NMS	-	Neuromuscular State
ANOVA	-	Analysis of Variance
PT	-	Position Task
STD	-	Standard Deviation
PHSG	-	Primary Haptic Steering Guidance model
LHSG	-	Look-Ahead Haptic Steering Guidance Model
FFT	-	Fast Fourier Transform
FRF	-	Frequency Response Function
SDLP	-	Standard Deviation of Lane Position
SRR	-	Steering Reversal Rate
HMI	-	Human machine interface

Chapter 1

Introduction

1. *Introduction*

1.1. The causes of vehicle accident and statistics

In 2009, the global status report on road safety described occurrence of vehicle accidents in 182 countries and revealed that 1.25 million deaths are attributed to vehicle accidents per year, and an additional 20 to 50 million of people are injured [1]. The United Nations General Assembly has declared the 2010-20 decade as the Decade of Action for Road Safety, aiming at promoting the road safety management capacity; improve the safety of roads and vehicles; enhance the behaviour of all road users; and strengthen post-crash vehicle. If immediate and efficient actions are not adopted, it is predicted that the number of fatalities caused by vehicle accident will reach 2.4 million worldwide in 2030 [1].

Most accidents are the consequence of human errors, which often involve drunk driving, driver distraction, speeding or driver drowsiness.

- A drunk-condition, which corresponds to driving while being under the influence of alcohol, or an intoxicated-condition, which corresponds to driving while being under the influence of drug, is likely to severely impair the condition of drivers. It has the effects of reducing their reaction time and their awareness of their surroundings and can also induce sleepiness.
- Driver distraction, which can be visual, manual and cognitive, diminishes the focus of the driver from the primary driving task. Internal events such as a mobile phone call, discussion with a passenger and screaming of a baby; or external events such as a street concert or visually attractive advertisement panel may lead to a shift in the focus of the driver.
- Speeding, which corresponds to an increase in the driving speed has been demonstrated to be the cause of an increase in occurrence of accident of vehicles and an increase of the severity of injuries caused by the crash. At high speed, the braking time is considerably augmented and the reaction time of driver, even if they present a normal neuromuscular condition, cannot react properly to the driving situation.
- Drowsiness, which is a fluctuating state of reduced awareness and impaired psychomotor performances, is likely to lead to crash of vehicle. An event of drowsiness, which may last few second, can coincide with a critical driving situation, in which driver would be able to react properly. Another cause of vehicle accident is the fatigue caused by lifestyle of drivers. Social and professional expectations induce an increasing daily workload, which leads to a decline in physical performance. Often, a decline in physical performances induces a condition of fatigued driving and may result in crash.

Furthermore, vehicle accidents also involve people who are not directly related to the driver. Indeed, more than 270 000 pedestrians pass away each year because of vehicle accident [2], accounting for 22% of the total 1.25 million road traffic deaths [1]. The occurrence of vehicle crash varies depending on countries and it was reviewed that only 28 countries, covering 7% of the world's population, took efficient actions for enhancing the road safety.

1.2. The example of Japan

To illustrate this issue, a detailed example on the vehicle accident occurrence in Japan is detailed in the Figure 1. These statistics includes fatalities among drivers, passengers of the vehicle, as well as pedestrians and cyclist.

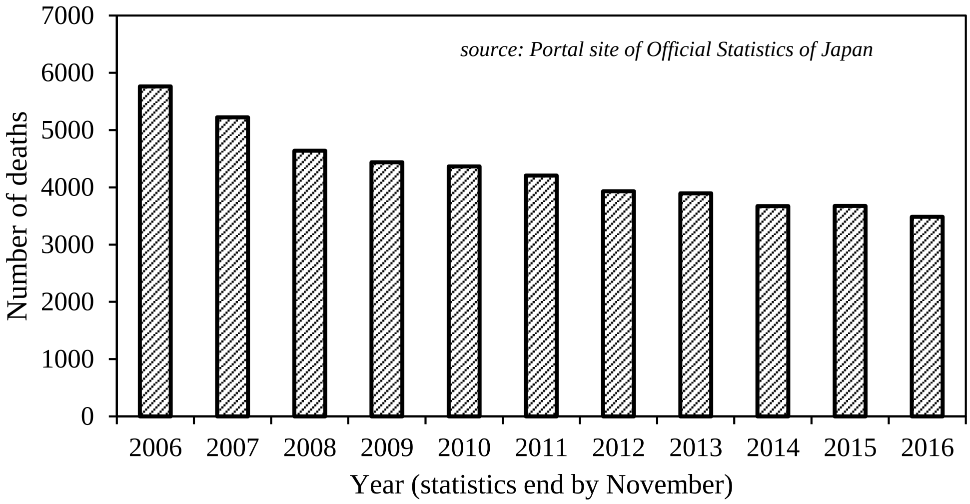

Figure 1. Number of fatalities in Japan related to car accident.

It can be observed that the number of fatalities is decreasing over the years thanks to efficient actions taken by the Japanese government in term of prevention. The statistics of vehicle accidents in Japan also proved that victims among pedestrians and cyclist account for a third of total number of road fatalities since 2006, which is higher than the review of Global Status Report on Road Safety by WHO.

Although a decrease is observed in the Figure 1, it is also reviewed that the number of road traffic deaths has plateaued since 2012, as the decrease in fatalities does not present a linear decrease. This review is the consequence of persisting dangerous behaviours that concerns violation of safe driving rule, such as failure to make safety check or failure to confirm traffic movements, or imprudent driving behaviours, such as road infringement, disregarding of traffic signal or failure to stop, as it can be observed on the legend of Figure 2.

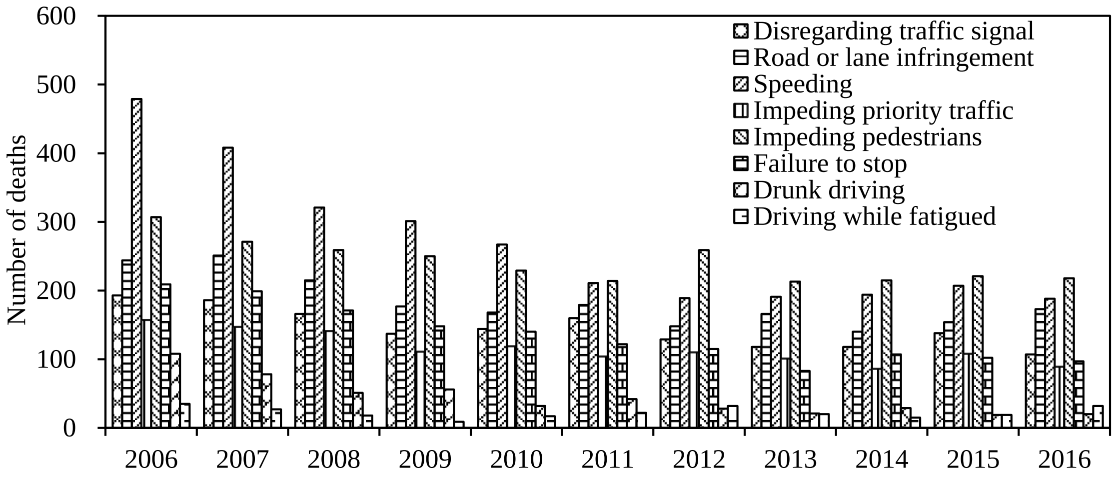

Figure 2. Cause of fatalities in Japan related to car accidents.

Although the global number of fatalities is decreasing over the years, which is consistent with the statistics of the Figure 1, certain behaviours remain the cause of constant numbers of fatalities over the years. Indeed, the number of accidents related to drunk driving and driving while fatigued remain high. These behaviours are related to the condition of the driver and can be consequently detected by monitoring systems, which can be embedded into vehicle. Furthermore, disregarding traffic signal, which can be related to the distraction of the driver, can also be detected by monitoring the condition of the drivers and by providing warning to improve their awareness to the environment, and make them respect the traffic rules.

In the Figure 3, the occurrence of fatalities related to vehicle accident depending on the age categories is investigated. It can be reviewed in the Figure 3 that all the categories of ages are affected by fatalities related to vehicle accidents, at the exception of the category of the 25-29 years old which seems to be, to some extent, preserved from road fatalities. The reason of decreased fatalities among this category of age can be explained by the sufficient driving experience and an optimal body condition.

The source of young driver's problems on the roads fundamentally lies in their lack of driving experience. Indeed, drivers with less than 2 years of driving experience, but ranging in age from 18 to upwards, committed the most traffic offences among all categories of driver [3]. Moreover, driver varying in experience from less than 2 years to more than 4 years did differ in the types and the numbers of committed driving offences [3]. This lack of experience will tend to encourage exposure to overly demanding driving conditions.

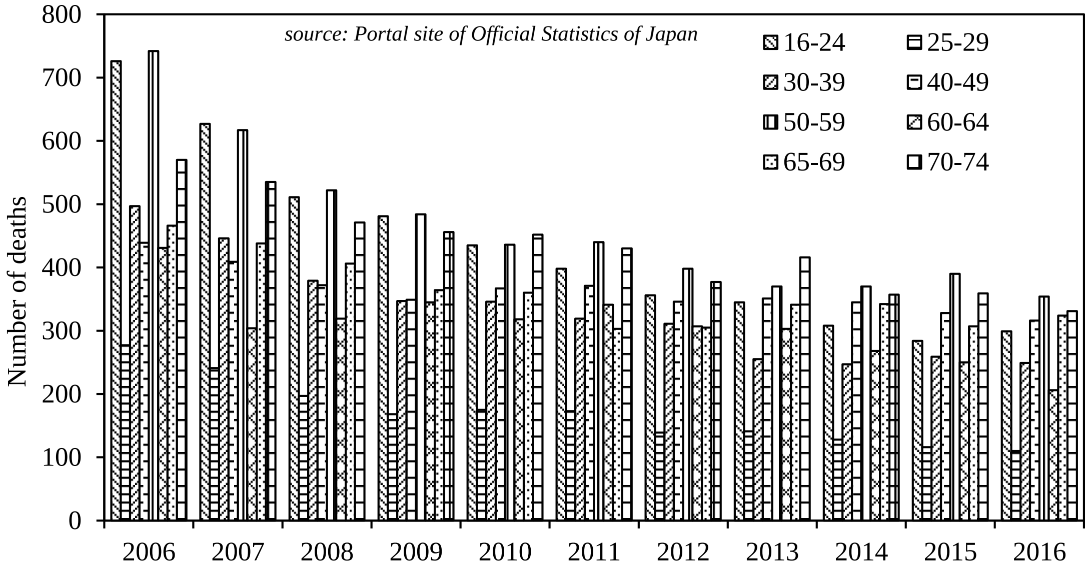

Figure 3. Number of fatalities in Japan related to car accidentds regarding the category of age.

The Figure 3 highlights the need of assistance for driver, independently from their age or driving skills. Taken together, the three previous Figures express that, even if the number of fatalities was successfully decreased by the prevention of the Japanese government and effort of drivers to respect driving safety rules but should be encouraged to continue toward an increase of the safety on roads in Japan.

1.3. Prevention of vehicle accidents: a social effort

In the world, millions of dollars have been invested toward enhancing to safety on roads but the occurrence of vehicle accident remains high. Consequently, the progress in driving safety should be pursed and improved. Prevention of vehicle accidents has been praised in most countries with examinations that includes driving safety learning, advertisement that warn about the human tragedies entailed by vehicle accident or legal actions against driver who do not respect the rules of safe driving. The conclusion of the Global Status Report on Road safety ordered by the World Health Organization recommended [2]:

- Adopting and enforcing new and existing laws to reduce speeding, curb drinking and driving, decrease mobile phone use and other forms of distracted driving;
- Putting in place infrastructure which separates pedestrians from other traffic (sidewalks, raised crosswalks, overpasses, underpasses, refuge islands and raised medians), lowers vehicle speeds (speed bumps, rumble strips and chicanes) and improves roadway lighting;
- Creating pedestrian zones in city centres by restricting vehicular access;
- Improving mass transit route design;
- Developing and enforcing vehicle design standards for pedestrian protection, including soft vehicle fronts;
- Organizing or further enhancing trauma vehicle systems to guarantee the prompt treatment of those with life-threatening injuries.

Governments need to take into considerations the needs of all road users as the need of vulnerable person (pedestrians, cyclists and motorcyclists) should also be taken in consideration when designing the road geometry and the traffic rules.

The establishment of traffic rules in regard of the driving speed, road width, safety distance between vehicles or weather conditions aim to limit potential driving mistakes aiming at enhancing driving safety. Whereas, reckless persons or drivers under the influence of agent that disturb condition, such as drowsiness or inattention, do no respect these rules. Drivers with a diminished perception of their environment present a decrease in their vigilance level, a decrease in the awareness of other vehicles in the surrounding, and a decrease in the vehicle control ability that entails danger for their own life and the lives of other people.

In order to reduce these occurrences, the proposition of self-driving vehicle has been proposed to remove human errors from the accident contributing factors. Whereas, their reliability is not sufficient since the level 5 of self-driving cars, which corresponds to a full automation of the control of the vehicle, is not achieved yet.

1.4. Existing assistance solutions and technologies

In the past decades, the carmakers developed various assistance systems that aim to provide information about the driver’s surrounding environment, such as parking camera or blind spot camera. They aim to improve the steering maneuvers performed by the drivers by refining the trajectories of the vehicle while performing a lane-change operation or managing the lane-keeping, for example. These progresses had been made possible by the improvements of camera technologies, especially, which can provide an accurate recording of the inside of the vehicle as well as the surroundings, which can be analyzed by the on-board computer. Depending on the level of automation, the decision system may provide either driving advice or interacting directly in the steering operations, in order to correct possible driving mistakes committed by the driver. These assistance systems can be divided into active assistant system and informative assistant system. The global functioning and the aim of these systems is illustrated in the Figure 4.

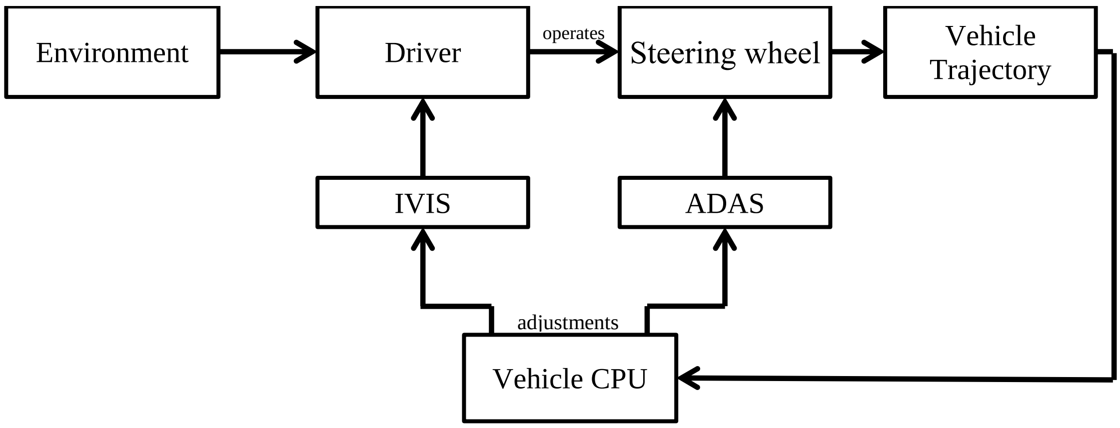

Figure 4. Simplified workflow of driving assistance systems.

Among active assistance technologies, which are categorized as Advanced Driving Assistance System (ADAS), the Electronic Stability Program (ESP) is feature that controls the trajectory of the vehicle, aiming at avoiding sideslip of the vehicle caused by excessive speed in curves with small radii or sudden trajectory changing [4]. It acts on the braking system as well as the gear system to smooth the driving and ensure non-sideslip condition.

Moreover, collision avoidance systems permit to decrease the frontal collision, which are often lethal for the driver and the passenger of the vehicle because of the violence of the impact between vehicles or with a wall. Their principle relies on the detection of incoming obstacles via a system of laser sensor that measures the distance between the vehicle and the obstacle, and either trigger an emergency braking operation or modify the trajectory of the vehicle to avoid the obstacle. It has been proved efficient in reducing crashes, especially among inattentive drivers [5].

Furthermore, the Adaptive Cruise Control (ACC), which corresponds to the monitoring of the speed of the vehicle, aiming at maintaining a safe distance from the vehicles ahead, has been proved efficient to reduce the vehicle accident occurrence on highways. It is especially efficient in cases where the braking distance is increased because of breakneck speed or for increased reaction time that can be caused by an impaired condition. It measures, with a system of radar, the distance and the relative speed between following vehicles in order to automatically adjust the distance between vehicles

Among informative assistance technologies, which are categorized as In-Vehicle Information System (IVIS), lane-departure warning system was developed to prevent the departure of the vehicle out of the lane, which can be caused by various factors such as the distraction of the driver caused by his or her conversation with the passengers, for example. It monitors the lateral position of the vehicle and provides a warning signal, which can be visual, auditory or vibrational, to the driver if the vehicle is likely to depart from the lane, unless a turning signal was activated by the driver beforehand. Furthermore, the blind spot monitoring of the vehicle has been proposed to remedy to the non-detection of the other vehicles located in the driver's side and rear, which can be hazardous if the driver of the vehicle decide to initiate a turn without awareness of other vehicle in the surroundings. It consists in a system of sensors that detect the vehicle in the surrounding of the vehicle and provide this information to the driver by notice signal, which can be visual, auditory, vibrational or tactile. Another example is the intersection assistant system, which provides information about the timing at which the drivers can drive through the intersection and provide information about the selection of the lane according to driver preliminary notice of direction. This system is often accompanied with a GPS system that provides the information of the configuration of the incoming intersection using a cloud database. If the driving behaviour seems dangerous, the intersection assistant system displays a warning signal and possibly trigger an emergency brake operation, independently from the initial operation of the driver. Although these systems have been proved to be efficient in reducing the number of vehicle accidents, they mainly focus on the consequence of the driving operations and their potential issues. A deeper understanding of the condition of the drivers and the knowledge of their intentions would permit to anticipate mistakes that the drivers could make and then improve the quality of the assistance, always aiming at enhancing the safety on roads.

1.5. The monitoring of driver as a solution for decreasing the number of vehicle accidents

The condition of the driver relates to the neuromuscular condition of the driver, which refers to the unconscious response of a muscle to a perturbation signal regarding dynamic joint stability. It can be subjected to variations since, fatigue, inattention or impaired motor coordination, for example, modify the physiological capacities of the driver, leading to a modification of steering actions and shifted reaction to driving events.

The monitoring of the condition of the driver appears to be a positive solution for improving the safety on roads. Moreover, it aims to maintain the driver in the driving decision loop, while correcting the driving mistake that the drivers may do. The method of transmission of the assistance can be applied to the steering wheel, the gas pedal or other ways of information transmission. Adopting this method entails that the condition of the driver should be known, which will be used as an indicator to decide the need of assistance of the driver. The influence of the steering assistance may vary for either correcting minor driving mistakes, if drivers do not present a reliable neuromuscular condition, or strongly interacting with the control of the vehicle, if an impaired neuromuscular condition is detected. The steering assistance may also come with auditory assistance if the driver is not aware of the danger he or she is facing caused by the degradation of the condition of the driver.

In the current situation, the monitoring of drivers can be achieved by the analysis of the evolution of driving performances and the analysis of facial features of drivers. Indeed, the monitoring of driving-related metrics such as the detection of lane departure, speed maintenance and control, large lateral deviations within the lane, or cessation of steering corrections can indicate the evolution of the condition of the driver. Indeed, the monitoring of lateral deviations of the vehicle has been used as an indication of the condition of the driver since the driver presenting an impaired condition tends to show degraded steering performances that leads to an increase of the lateral deviation of the vehicle [6]. Furthermore, the Time-to-Line-Crossing (TLC) has been employed to measure the time for the vehicle to possibly go over the safe boundaries of the road, which is used for knowing the need of assistance required by drivers [7]. It indicates the time required for observing a lane-departure occurrence if the driver maintains the same steering behaviour. Moreover, the monitoring of the Standard Deviation of Lane Position (SDLP) has been widely used to describe the evolution of driving performance as an indicator of the need of assistance required by drivers [8][9]. At the opposite of the TLC, this variable does not necessitate having a GPS localization system embedded since the monitoring of the trajectory of the vehicle is calculated regarding the current lateral position of the vehicle compared to the ideal trajectory. It can be measured via laser sensors, which makes it cost-friendly, that can acquire the lateral position of the vehicle. It is suggested that larger SDLP imply large steering operation from the ideal trajectory and may increase the probabilities of accidents.

Moreover, the analysis of facial features of the driver has been used as an indicator of the condition of the driver. Indeed, many studies have concluded that eye tracking is a valid measure of a degraded neuromuscular condition and provides various types of information that can reveal the physiological state of the drivers [10]. Recent progress in machine vision research and advances in computer hardware technologies have made the measurement of eyelid movements accurately and in real time using video cameras possible. These methods are often used for detecting driver drowsiness or driver distraction, since drowsy drivers tend to show typical eyelid patterns, and distracted drivers do not look at the road.

Whereas, these existing solutions do not provide, at the exception of camera systems, an accurate description of the condition of the driver since they investigate the consequence of the condition of the driver on the driving behaviour, instead of monitoring the driver directly. Assessing the condition of the driver state based on physiological sensors data or embedded mechanical sensors seems to be worth of investigation to enhance safety on roads.

1.6. Motivation of this research

This dissertation focuses on the proposition of an innovative method for monitoring the condition of the driver and an approach to influence the condition of the driver, using existing steering technologies.

Based on the review of previous studies concerning assistance systems and the development of technologies by carmakers in term of driving safety, it is apparent that the current solutions that aim to ensure the safety of drivers in various driving situations do monitor the effects of the condition of the driver on driving behaviour instead of monitoring the condition of the driver. The advantage of monitoring of the condition of the driver is to anticipate potential driving mistakes by influencing the condition of the driver, aiming at increasing the awareness of the driver to the surrounding environment and improving driving skills. As a result, the investigation in this dissertation concerns:

1. A method for acquiring information about the condition of the driver.
2. Finding a suitable steering technology that can assist driver efficiently, without inducing driving burden.
3. A method to influence the condition of the driver via the proposed steering technology.
4. The investigation of the benefits and the disadvantages of testing the proposed method on the condition of the driver and the steering performances.
5. A decision on the viability of the proposed method to monitor the condition of the driver.

Chapter 2

State of art

2. *State of Art*

2.1. Introduction to shared control systems

The challenge in designing an efficient driving assistance system has been present in automotive controls research for over the last decades. In order to remedy to vehicle accident occurrence and diminish driving burden, assistance systems have been developed. Among them, two groups must be distinguished.

On one hand, Advanced Driving Assistance System, so-called ADAS, intends to assist drivers by monitoring their actions within the pre-defined boundaries. Alerts signals might be used if the pre-defined boundaries of the assistance system are reached and the assistance actuators will be triggered to aid the drivers. The assistance can be provided through the steering wheel and the gas pedal, for example. The aim of these methods is to increase the level of automation, also referred as SAE autonomy level, in order to relieve the drivers from driving tasks, automating driving without human intervention. Car maker such as Tesla, which its Model 3 is equipped with a driver-facing camera, requires the drivers to keep their hands on the steering wheel and monitor the actions of the vehicle. It corresponds to level 2 of SAE autonomy level. Having additional method for monitoring the driver permit to increase the SAE autonomy level, improving the automation of the car.

On the other hand, In-Vehicle Information System, so-called IVIS, aims to support drivers by gathering information about the surrounding environment of the vehicle and displays informative data about surroundings of the vehicle, or incoming traffics jam, for example.

In the recent years, steering shared control, which belongs to the ADAS category, has been proposed as a solution for supporting drivers while maintaining them in the steering decision loop. Shared control, when dedicated to the steering wheel, is a feature that can drastically enhance road safety by assisting drivers by enhancing the steering stability during challenging driving situations. It has been proved in previous studies that the development of an efficient driving assistance system requires neither to interfere with the intentions of the drivers nor to disturb him or her from the driving task [11][12]. Indeed, a distracter task that requires the same perceptual or motor resources as the driving task appears to impair driving performances. The source of a distracter task is often visual or audio [13][14]. A visual distraction occurs when the driver neglects to look at the road and focuses instead on another target for an extended period of time. An auditory distraction occurs when the driver attention is caught by an audio signal, such as radio or a conversation with passengers. An increase in the mental workload of the driver often leads to a decrease in driving performance and possibly vehicle crashes. Indeed, the National Highway Traffic Safety Administration reported that the 22% of drivers aged 16 to 25 years who were involved in fatal crashes, were reported to have been distracted at the time of the crash [15]. Moreover, it was demonstrated that the in-vehicle task of interacting with an entertainment system can affect measures of driving performance such as preparedness to react to unexpected hazards (e.g. to slow down when a pedestrian suddenly crosses the road in front of the vehicle) [13]. Therefore, avoiding driver distraction is essential for ensuring the driving safety.

To transmit information to the drivers, shared control feedbacks seem to be the safest way to inform drivers with a minimum of disturbance of focus [12]. Indeed, feedbacks based on shared control theory have been shown to be very promising not to interfere with the focus on driving since they act on the operation tool that the driver is interacting with, such as the steering wheel or the gas pedal [16][17][18].

2.2. Haptic steering guidance control

Steering haptic steering guidance control is a method that falls within the scope of Human-Machine Interface (HMI) and allows both the human and the steering assistance system to exert forces on the steering wheel, of which the output is a direct input to the haptic steering guidance control algorithm, creating a close-loop control of the steering wheel. It aims to maintain the driver in the steering decision loop, while providing continuous trajectory assistance in order to implement a smooth transfer of the control authority [19][20]. Moreover, it presents a quality of being scalable to a broad spectrum of applications and industries. Recently, it has been used for medical, automotive and aviation applications [21][22].

For automotive related applications, haptic steering guidance control is an assistance feature that guides drivers through a predetermined trajectory, providing motorized feedback via application of guidance torque.

Abbink et al. applied shared control on a gas pedal in order to investigate the influence of haptic gas pedal feedback on driver control behaviour during vehicle-following [16]. Moreover, Tsoi et al. proposed a steering haptic steering guidance architecture that permits to perform a shared control of the vehicle by providing a continuous haptic torque on the steering wheel to optimize lane keeping [17].

A description of the interaction of the driver with the steering haptic steering guidance system and the vehicle dynamics is presented in the Figure 5.

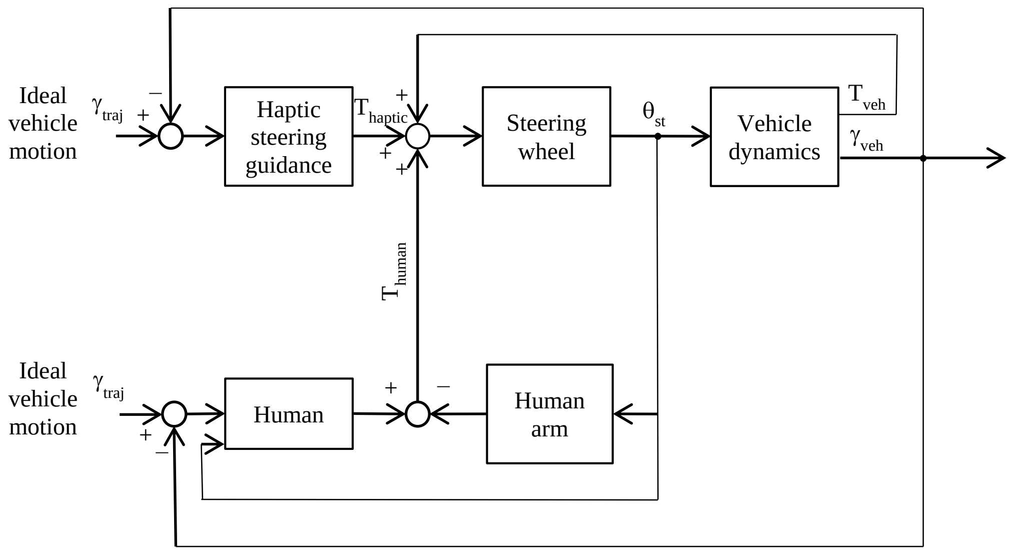

Figure 5. Interaction of the driver with the steering haptic steering guidance system and its environment.

T_{haptic} is the torque exerted by the haptic steering guidance system in reaction to a perturbation torque T_{veh}, or to the self-aligning torque, which comes from the friction dynamic of the tires with the road, or imply a steering shared control of the vehicle that is also control by the driver torque T_{human}. θ_{st} denotes the steering wheel angle, γ_{traj}, the ideal trajectory characteristics and γ_{veh}, the characteristics of the vehicle trajectory, which include the lateral position and lateral velocity of the vehicle and its yaw angle and yaw rate.

Within the frame of haptic shared control, the requirements that are needed for avoiding human-automation interferences are based on the haptic model design, the haptic intensity, as well as timing at which haptic steering guidance is applied to the steering wheel.

From the context of human control, feedbacks provided by haptic steering guidance control were demonstrated effective for increasing the driving safety measured with different indicators [23][24]. Indeed, it was observed that haptic steering guidance control improved the performance of drivers in path following, obstacle avoidance tasks, and curve negotiation during driving tasks. Marchal-Crespo et al. presented the improvement made by a haptic-guided subject group, which presented less steering errors while driving, due to their ability to predict the timing of initiation of the steering movement while entering a curve [23]. In another study, Marchal-Crespo et al. proposed a motor learning method using haptic steering guidance to produce an even better motor learning timing for curves [25]. Furthermore, a study made by Tsoi et al. established that lane maintenance performance improved during reduced control activity with haptic steering guidance [17]. Finally, Brandt et al. designed a collision avoidance system based on the cooperation between the driver and the haptic steering guidance system. Their path planning algorithm showed efficient performances based on collision reduction [24].

Although haptic steering guidance control can have a positive impact on the driving performances, some studies that investigate the effects of haptic steering guidance control application on drivers are mitigated about the risk inherent to this technology. Indeed, haptic steering guidance control can also 'perturb' drivers or even induces inattention, increasing the risk of automobile accidents in specific cases. Furthermore, applying long-term haptic steering guidance systems may cause drivers to become over-confident, relying on the steering assistance and present decreased aptitude for handling complex driving situation.

Indeed, Lee and Choi analysed the results of an experiment where subjects had to memorize spatial patterns on a benchmark while haptic steering guidance was applied and reviewed that the performance of participants for reproducing these spatial patterns were severely degraded when haptic steering guidance was deactivated [26].

These contradictory examples prove that monitoring the drivers using haptic steering guidance control is beneficial but might also induces driving issues, which must be investigated to build a reliable steering haptic steering guidance control system that can help drivers presenting a deprived condition.

2.2.1. Primary haptic steering guidance model

For designing a haptic steering guidance model, six driving variables, which are the lateral deviation, lateral velocity, yaw angle, yaw rate, the steering wheel angle and steering wheel angular velocity, are used. Whereas, a recent study investigated the relationship between steering wheel angle and yaw rate and proved that an equivalence can be made between these variables within a certain steering angle range [27].

As a result, four metrics, which are lateral deviation, lateral velocity, yaw angle and yaw rate, are used to design a haptic steering guidance model. In the literature, two main models of haptic steering guidance have been developed, which can be named as 'Primary haptic steering guidance' (PHSG) and 'Look-ahead haptic steering guidance' (LHSG). In the Figure 6, the characteristics of the PHSG are presented. This model monitors the position of the vehicle compared to the closest point belonging to the target trajectory, based on the monitoring of the current lateral position and lateral velocity of the vehicle, and the monitoring of the yaw angle and yaw rate of the vehicle. The equation that rules the steering feedbacks of the haptic steering guidance model can be theorized as

$$u = k \cdot (\mathrm{a}_1 \cdot e_y + \mathrm{a}_2 \cdot \dot{e}_\mathrm{y} + \mathrm{a}_3 \cdot e_\theta + \mathrm{a}_4 \cdot \dot{e}_\theta), \quad (1)$$

where u is the haptic torque applied on the steering wheel, k is the coefficient that rules the amplitude of the haptic torque, a_1 and a_2 are the coefficients that affect the lateral deviation and lateral velocity of the vehicle e_y and $\dot{e}_y$, a_3 and a_4 are the coefficients that affect the yaw angle and yaw rate of the vehicle e_θ and $\dot{e}_\theta$. The coefficients a_i of the equation (1) can be changed to modify the design of the steering feedbacks depending on the need of the driver, the geometry of the road and the driving situation.

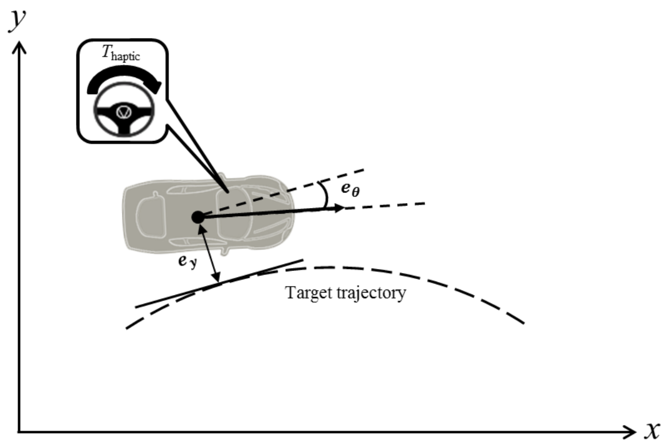

Figure 6. Primary haptic steering guidance model.

The pros and cons of using PHSG model are presented in the section 2.2.3 and compared with the pros and cons of using LHSG model. This model of haptic steering guidance has been introduced in studies that aims to monitor the lane keeping of the vehicle [28][29].

2.2.2. Look-ahead haptic steering guidance model

A second model of haptic steering guidance, named 'Look-ahead haptic steering guidance', is presented in the Figure 7. This model considers an incoming point of the desired trajectory in order to design the steering feedbacks according to this 'look-ahead' point. It monitors the characteristics of the incoming trajectory of the vehicle and provide steering feedbacks based on the characteristics of a look-ahead point of the desired trajectory. It is based on the monitoring of the lateral deviation and lateral velocity of the look ahead trajectory, and the monitoring of the yaw angle and yaw rate of the look ahead trajectory. The equation that rules the steering feedbacks of LHSG can be theorized as

$$u = k \cdot (a_1 \cdot e_{y(far)} + a_2 \cdot \dot{e}_{y(\mathrm{far})} + a_3 \cdot e_{\theta(\mathrm{far})} + a_4 \cdot \dot{e}_{\theta(\mathrm{far})}), \quad (2)$$

where u is the haptic torque applied on the steering wheel, k is the coefficient that rules the amplitude of the haptic torque, a_1 and a_2 are the coefficients that affect the lateral deviation and lateral velocity of the look-ahead trajectory $e_{y(far)}$ and $\dot{e}_{y(far)}$, and a_3 and a_4 are coefficients that affect the yaw angle and yaw rate of the look-ahead trajectory $e_{\theta(far)}$ and $\dot{e}_{\theta(far)}$. Coefficients a_i of the equation (2) can be changed to modify the design of the steering feedbacks depending on the need of the driver, the geometry of the road and the driving situation.

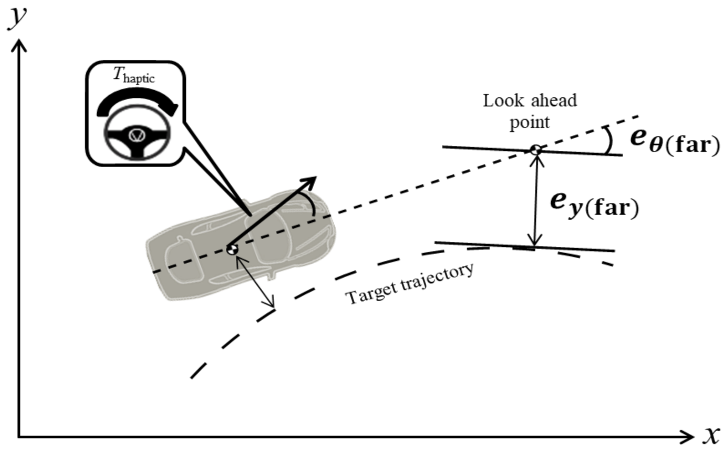

Figure 7. Look-ahead steering haptic steering guidance model.

This model of haptic steering guidance has been introduced in studies that aims to steering behaviour in curves to smoothen the trajectory of the vehicle [30][31].

2.2.3. Combination of both models

The selection of the haptic model mainly depends on the aim of designed steering feedbacks as the benefits of the two different models mainly depend on the shape of the road. The combination of the spatial characteristics of the PHSG and LHSG are presented in the following Figure 8.

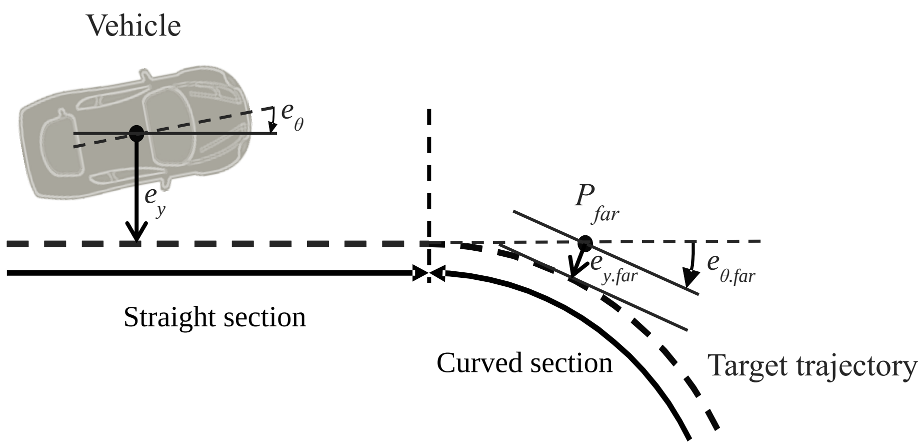

Figure 8. Advanced haptic steering guidance model based on PHM and LHM.

On one hand, the PHSG presents a robust monitoring of the trajectory of the vehicle while driving in straight sections of roads. Indeed, it is monitoring the current position of the vehicle with a reference point that remains linear in the spatial trajectory of the vehicle compared to the target trajectory. Whereas, when the vehicle enters a curve, the PHSG shows decreased performances to aid drivers since haptic steering guidance system reacts to sudden changes in the curvature of the target trajectory and provides very dynamic feedbacks that can perturb the driver. On the other hand, LHSG shows reduced efficiency during straight sections, compared to the PHSG, but presents a strong reliability during curve since it considers the incoming trajectory to computed optimal steering assistance. Whereas, if the look-ahead point is too far from the position of the vehicle, the efficiency of the haptic steering guidance might decrease because of inadequate assistance torque provided on the steering wheel. Including all these characteristics in the same model, which are the lateral deviation and lateral velocity, the yaw angle and yaw rate, of the current position of the vehicle and the lateral deviation and lateral velocity, the yaw angle and yaw rate of the look-ahead position point of the desired trajectory cannot permit a stable and smooth control of the wheel since the derivative terms of the characteristics may interfere between themselves, which would decrease the quality and the pertinence of the steering feedbacks. During straight sections, the vehicle can be monitored easily with the PHSG since it considers the lateral deviation, the yaw angle, as well as their derivatives which increases the quality of the steering feedbacks thank to an increased number of monitored variables. Whereas, when the vehicle enters curved sections, the change in the curvature of the road induces an error in the steering feedbacks that entails sudden instability in the monitored variables, which are the lateral deviation, the yaw angle, and their derivatives. If the incoming curvature of the road is known, which is required for using LHSG, the steering feedbacks system can take it into account and implement a smoother application of the corrective torque. As a result, an ideal haptic steering guidance control model takes into consideration of the curvature of the road to apply either steering haptic feedbacks based on the PHSG model if the road is straight, or steering haptic feedbacks based on the LHSG model if the road presents curvature.

2.3. The importance of condition of the drivers in the design of haptic steering guidance

Haptic steering guidance control permits to provide a continuous assistance to the driver, insofar as the condition of the driver is not impaired. The influence of haptic assistance systems has been evaluated in terms of safety and steering stability, but its effect on human driving behaviour has not been sufficiently explored. The optimal choice of haptic intervention depends on many factors, such as the design of the haptic system, traditional human factors considerations, driving scenarios and the neuromuscular condition of the driver. Consequently, it is then important to determine if haptic assistance improves the state of the driver. As various criteria can affect the condition of the driver combined with the fact that haptic steering guidance cannot differentiate the driving aim of a normal driver from the aim of a driver presenting an impaired condition, the intention of the driver should be monitored not to interfere with the haptic steering guidance control system. If incorrectly parametrized, the actions of the drivers might be negatively affected by haptic steering guidance and steering haptic feedbacks might worsen the condition of the driver. Therefore, to understand the intentions of the driver, the assistance system must monitor the condition of the driver.

Chapter 3

Detection of impaired neuromuscular condition and its application to haptic steering guidance

3. *Proposal: Detection of impaired neuromuscular condition and its application to haptic steering guidance*

The recurrent problem of driving assistance systems is that most of sensors that could be used to acquire the condition of the driver are invasive. The term “invasive” in the automotive field means that the method used to acquire information is using devices that must be worn by the drivers, such as glove, scapula sensors or outfits that include sensors. The inconvenience of these devices lies in the time required for wearing these devices and the design of these sensors, which is annoying for a daily use. This explains why vehicle technologies can difficultly acquire information about the NMS of drivers that can indicate their driving intentions and their conditions. In the Figure 9, an example of EMG (Electromyography) sensors attached to the skin is presented. They can evaluate and record the electrical activity produced by skeletal muscles.

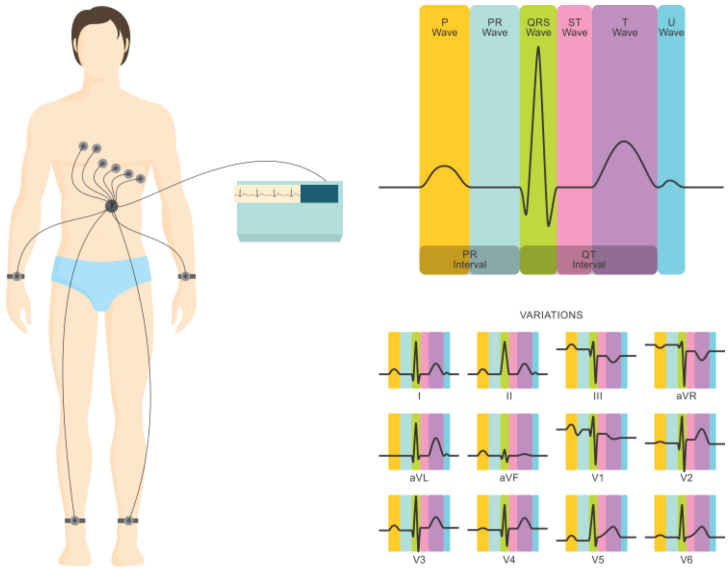

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Figure 9. Acquisition of EMG signals of muscles with sensors and shape of the signals.

Using such sensors is not convenient when designing an assistance system that can provide feedbacks based on the electrical activity of the muscle since the drivers must attach these sensors before driving. Whereas, recent improvement in the design of some sensors makes them less invasive and more convenient for a daily use. Indeed, it is now possible to acquire the grip pressure applied on the steering wheel without using gloves, which was mandatory in the past. An innovative steering wheel with hand pressure sensing areas has been developed in 2015 by Lisseman, Andrews and Bosch, which its main advantage is the recognition of the hand location on the steering wheel [32]. This system relies on a plurality of pressure sensors located in the steering wheel. If two sensing regions are activated at the same time, computational system recognize that driver is holding the steering wheel with two hands. As a result, it increases the degree of accuracy in term of grip pressure level. Indeed, previous steering grip sensors could not recognize the difference between handling the wheel with one hand (manipulating the radio set) and two hands.

To couple the measure from sensors with a mathematical human model, human control and its inherent limitations have been investigated recently to provide comprehensive models of the behaviour of the different limbs of the driver involve in driving operation and acquire the neuromuscular condition of the driver. These mathematical models, which describe the adaptive behaviour of the arm, mainly, present the interaction of various bio-mechanical properties.

In the following sections, mechanical arm admittance, a metric that describes the neuromuscular condition of the driver, is presented with different approaches. Mechanical arm admittance is an estimation of arm stiffness of drivers and has been described as a robust indicator of state of the driver by many studies [33][34][35]. The interactions of the driver with the steering wheel can be represented as seen in the Figure 10. The drivers who are perturbed by a disturbance torque T_{pert}, which their model is represented by mechanical arm admittance Υ_{adm}, output a torque T_{driver} that results in a steering angle $\theta_{st.}$. They are instructed to maintain the vehicle close to the ideal trajectory represented by the referring steering angle $\theta_{ref.}$.

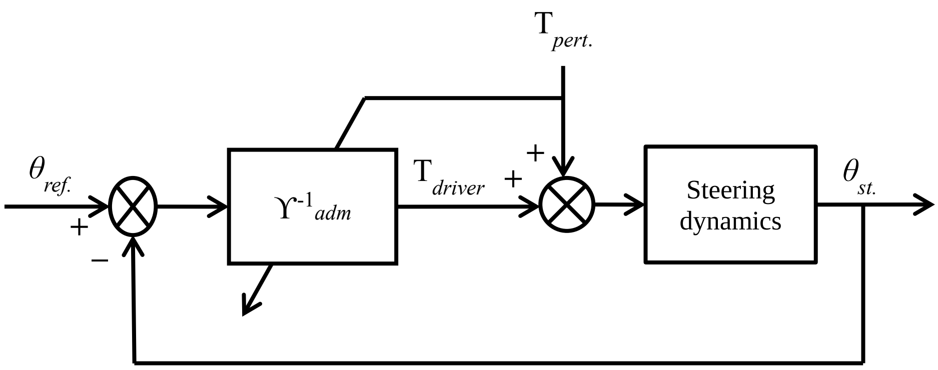


Figure 10. Representation of the human steering control via mechanical arm admittance.

3.1. Mechanical arm admittance as an indicator of driver condition

This section aims to propose a method to acquire the NMS of the driver via the estimation of mechanical arm admittance.

3.1.1. Estimation of mechanical arm admittance using driving-related variables

In driving terms, mechanical arm admittance (MAA) illustrates the ability of the driver to react to steering perturbations. Schouten et al. described human posture control, which is characterized by minimization of deviation from a reference position with mechanical arm admittance [36]. Participants must actively control the steering wheel in order to preserve the stability of the vehicle. Estimation of mechanical arm admittance usually requires performing the so-called classic Position Task (PT). A PT corresponds to the estimation of mechanical arm admittance featuring an active driver behaviour, i.e., participants are asked to minimize angular position while steering perturbations are applied to the steering wheel.

In the Figure 11, you can observe a basic representation of the steering interaction of the driver with a steering disturbance, resulting in a steering wheel angle variation within the frame of a PT performance. The trajectory of the vehicle can be straight, so the target steering wheel angle is constant, or with curves. With the occurrence of road curves, the driver must adapt his or her steering control to fit the desired steering angle.

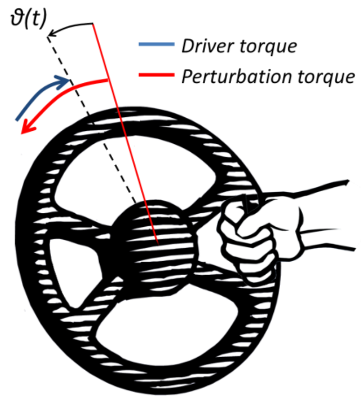


Figure 11. Simple representation of the interaction between the action of the driver, the steering perturbation and the resulting steering wheel angle.

In real driving situation, the steering wheel angle is influenced by both perturbation torque, which can be caused by side pressure caused by wind or degraded road condition, and driver torque, which is applied by the driver in order to follow a desired trajectory. The minimization of the steering wheel angle aiming at fitting the ideal steering wheel angle, which varies according to the curvature of the road, corresponds to the will of maintaining a safe distance with the side of the road. This interaction is used in the estimation of mechanical arm admittance to assess the capacity of drivers to resist to perturbations. Mechanical arm admittance is analysed in three parts: amplitude, phase and coherence. The amplitude of the MAA is used to express the NMS of the driver. The phase of MAA is used to investigate the type of NMS model. The coherence of MAA is used to assess the quality of the estimation. The equation of mechanical arm admittance focuses on the dynamic relationship between driving input and driver output and can be theorized as

$$\Upsilon_{adm}(f) = \frac{G_{d\theta}(f)}{G_{df}(f)}, \tag{3}$$

where $G_{d\theta}$ (*f*) is the cross power spectral density between the steering disturbance torque *d* and the steering wheel angle *θ*, and G_{dt} (*f*) is the cross power spectral density between the steering disturbance torque d and the driver steering torque t. Regarding equation (1), when the value of the amplitude of mechanical arm admittance is low, it means that participants input an accurate torque feedback to steering perturbations, resulting in a high resistance to perturbations. Oppositely, when the value of the gain of mechanical arm admittance is high, it means that participants input a weak torque feedback to steering perturbations, resulting in a low resistance to perturbations. Abbink described this phenomenon by explaining the role of muscle co-contraction in the resistance to perturbation [37]. Indeed, when drivers resist the forces, they will use their reflexes together with high levels of muscle co-contraction. A higher level of muscle activation increases the muscle stiffness and viscosity, thereby increasing the joint's instantaneous resistance to perturbations, which is showing small admittance amplitude.

Cross power spectral analysis allows determining the relationship between two-time series as a function of frequency. It corresponds to the Fourier transform of cross correlation between two-time series. Cross correlation is a measure of similarity of two series as a function of the lag τ of one relative to the other. For continuous functions *f* and *g*, the cross correlation is defined as

$$(f \cdot g)(\tau) = \int_{-\infty}^{\infty} f^{*}(t) \cdot g(t+\tau) dt \,, \tag{4}$$

where f^* denotes the complex conjugate of *f* and τ is the lag. In more explicit terms, Computing the cross spectral density between two signals means to know the shared power between these two signals. The linearity of the processed data is checked using square coherence, which varies from 0 to 1 (0 represents a full noise system and 1 represents a free noise system). The coherence of mechanical arm admittance is defined as

$$\Upsilon_{Coh} = \frac{G_{d\theta}(f)^2}{G_{dd}(f).G_{\theta\theta}(f)}, \tag{5}$$

where $G_{d\theta}(f)$ is the cross power spectral density between the disturbance torque *d* and the steering wheel angle θ, $G_{dd}(f)$ is the autoregressive power spectral density of the disturbance torque *d*, and $G_{\theta\theta}(f)$ is the autoregressive power spectral density of the steering wheel angle θ. Autoregressive power spectral density represents the computation of the cross correlation of the same time series. For practical application of this metric to automotive application, it was demonstrated that dominant human power lies in a frequency range from 0.6 to 5 Hz for cyclic body movements [38]. Therefore, the analysis of mechanical arm admittance is adapted to this frequency range as steering operations are cyclic. Moreover, for numerical considerations, spectral densities are averaged over five adjacent frequencies to reduce the variance of estimations and increase the coherence of results [39].

3.1.2. Estimation of mechanical arm admittance using bio-mechanical properties

In human factors term, mechanical arm admittance has been described by Forbes et al. by identifying reflex behaviour of the arm while performing a PT for the estimation of characteristics of the upper limb [40]. The different mechanism playing a role in the steering operations can be theorized as

$$\Upsilon_{adm} = H_{arm}(s) + H_g^{-1}(s), \tag{6}$$

with $H_g(s)$, the grip dynamics, which is described as

$$H_g^{-1}(\mathrm{s}) = b_g \cdot s + k_g, \tag{7}$$

and $H_{arm}(s)$, the arm dynamics, which is described as

$$H_{arm}(s) = \frac{1}{m \cdot s^2 + \beta \cdot s + k + (k_a \cdot s^2 + k_v \cdot s + k_p) e^{-\tau_d \cdot s} \cdot H_{act}(s)} \quad (8)$$

and $H_{act}(s)$, the activation dynamics is modelled by a second order

$$H_{act}(s) = \frac{1}{1 + \frac{2 \cdot \beta}{\omega_0} s + \frac{1}{\omega_0^2} s^2}, \quad (9)$$

The signification of the different coefficients used in the equation (6) to (9) are described in the Table 1. These equations have been widely used to describe the variations of mechanical arm admittance in the frequency domain using bio-mechanical terms [34][36][40]. Experimental configuration, aiming at the estimation of MAA using bio-mechanical coefficient, would measure the muscle activity, muscle force and position of the joint of the upper limbs with sensors to extract the relevant bio-mechanical coefficients from the analysis of data. The Table 1 describes the average values of mechanical arm admittance coefficients of several studies that used the equation (6) as a reference. These coefficients describe the characteristics of the upper limb featuring underlying mechanisms of the arm and the hand, as they describe the intrinsic model of the grip mechanism and the intrinsic model of the arm mechanism via the equations (7) and (8). The coefficients of Table 1. are taken from the study made by Schouten et al. [36] (data set No.1), Forbes et al. [40] (data set No.2), and de Vlugt et al. [34] (data set No.3), respectively.

Table 1. Human factors related variables.

			Data set No.1	Data set No.2	Data set No.3
m	[kg]	arm mass	2.02 (+/-0.39)	2.23 (+/-0.39)	1.88 (+/- 0.29)
β	[Ns/m]	muscle damping	32.5 (+/-10.1)	64 (+/-14)	37.3 (+/-6.3)
k	[N/m]	muscle stiffness	382 (+/-181)	506 (+/-305)	733 (+/-175)
b_g	[N/m]	grip damping	228 (+/-94)	339 (+/-151)	178 (+/-45.5)
k_g	[kN/m]	grip stiffness	11.7 (+/-6)	31 (+/-12)	14.9 (+/-0.05)
k_a	[Ns^2/m]	acceleration feedback gain	2.3 (+/-0.5)	6.6 (+/-1.8)	n/a
k_v	[Ns/m]	velocity feedback gain	37.4 (+/-16.3)	137 (+/-40)	35 (+/-n/a)
k_p	[N/m]	position feedback gain	91 (+/-145)	1348 (+/-540)	100 (+/-n/a)
τ_d	[ms]	neural time delay	28.4 (+/-4.9)	30 (+/-4)	36.1 (+/-5.2)

By replacing these coefficients in the combination of equation (6), (7) and (8), the amplitude of mechanical arm admittance can be plotted. For plotting the three-different amplitude of mechanical arm admittance, which are displayed in the Figure 12, the three set of data of Table 1 are used in the equations listed in Table 1.

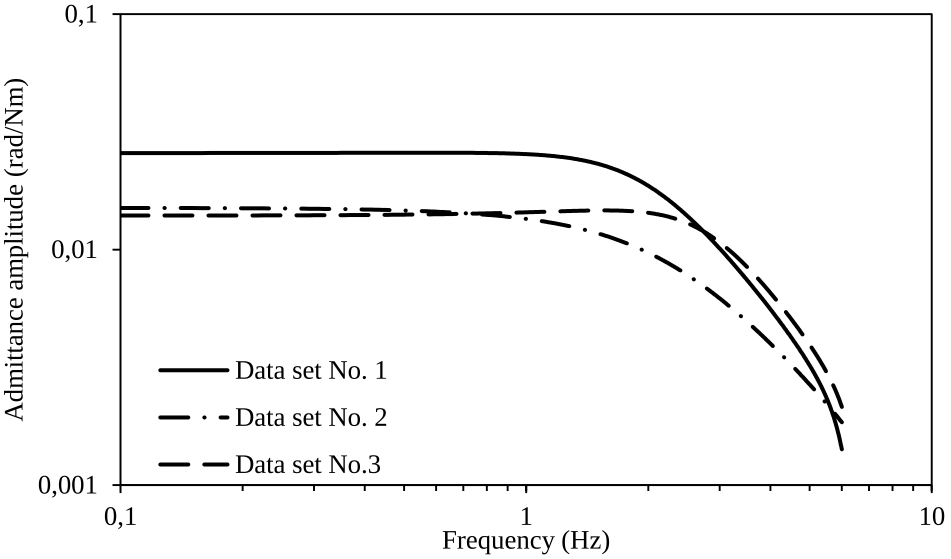


Figure 12. Theroetical amplitudes of mechanical arm admittance depending on participants bio-mechanical coefficients.

It can be observed in the Figure 12 that the three set of data present differences in amplitude, which indicates a difference in the neuromuscular condition of the driver. Moreover, it can be observed that the three curves adopt a similar behaviour as the frequency increases, as they present a decrease in amplitude. Furthermore, it can be observed that the amplitude of mechanical arm admittance presents similarities with a model of a second order mass-spring-damper. Indeed, it is often cited in the literature that the motion of a limb while performing a position task can be described as a second-order mass-spring-damper model as the limb has been stimulated by oscillatory motions, and impact motion, that include the features of stiffness, damping, viscosity, natural frequency, and moment of inertia. However, a resonance is not observed since the mechanisms involved in the motion of the upper limb are complex and cannot be simplified to a second-order mass-spring-damper model. In order to assess that influence of the coefficient of the stiffness of the arm on the amplitude of mechanical arm admittance, the data set No.1 was used as reference and its stiffness was modified.

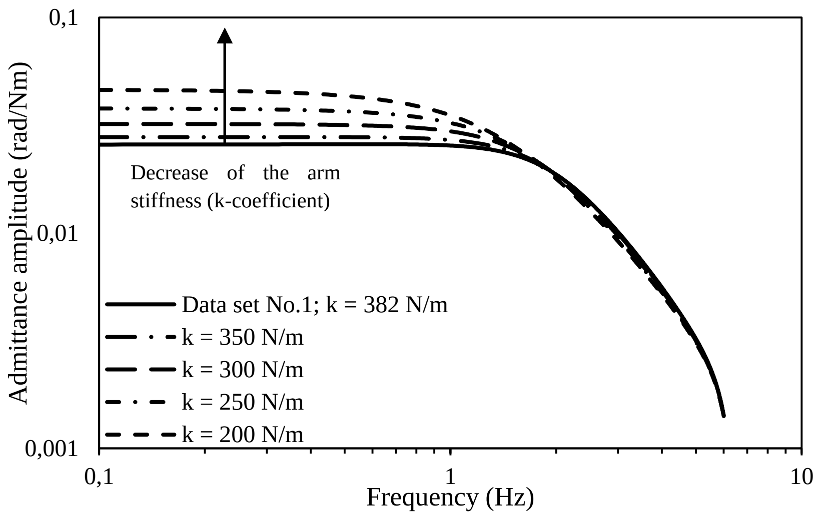


Figure 13. Theoretical effects of decrease of stiffness of the arm on MAA.

In the Figure 13, it is assumed that the coefficients of the Data set No.1 of the table 1 are constant at the exception of the arm stiffness coefficient that is modified to investigate its effect on amplitude of mechanical arm admittance. It is seen that the amplitude of mechanical arm admittance tends to increase with the decrease of the arm stiffness. It confirms the statement made in the section 3.1.1, which states that low amplitude of mechanical arm admittance expresses high stiffness of the arm and high resistance to perturbation, and high amplitude of mechanical arm admittance expresses low stiffness of the arm and low resistance to perturbations. As a result, drivers presenting low amplitude of mechanical arm admittance are preferred since they present a favourable neuromuscular condition with accurate muscle coordination and high capacity to avoid accidents.

3.1.3. Conclusion on the method for estimating mechanical arm admittance

It was presented in the two previous sub-sections that mechanical arm admittance is a metric that can be estimated using both driving-related variables, i.e. driver torque, steering angle and perturbation torque, and bio-mechanical coefficients, i.e. arm stiffness, arm damping, position feedback, etc, as presented in the Table 1.

It demonstrates that mechanical arm admittance is a reliable model of the upper limb of a driver that can describe the arm reactions while performing steering operations, using characteristics of different domain. As a result, it can be used as a reliable metric to assess the NMS of the drive.

In the rest of this dissertation, a driving simulator is used to perform driving experiment that aim to analyse the condition of the driver using MAA using driving-related variable, which refers to the explanations presented in the sub-section 3.1.1. However, the relevance of the estimation of MAA using bio-mechanical properties of the limb will be used in some cases as a comparison to estimate the quality of the estimation.

3.2. Haptic steering guidance application to influence the condition of the driver

This section aims to propose a method to influence the NMS of the driver using haptic steering guidance control.

3.2.1. Application of haptic steering guidance feedbacks to stimulate the driver and influence the condition of the driver

In the section 2.2, the PHM and LHM are presented, and differences in performances and their relevancies in driving situations are explained. To influence the condition of the driver, stimulating the Frequency Response Function (FRF) of the driver using tools that the driver is interacting with seems relevant. Indeed, it was demonstrated in previous study that applying vibrations to the driving seat or auditory warning might perturb the driver and they would overreact to the stimulation, resulting in another kind of impaired driving, where the driving stability is shifted with the application of large steering corrections by the driver [41].

Consequently, the application of haptic feedbacks on the steering wheel seems appropriate to influence the condition of the driver since haptic steering guidance control considers the steering operations of the driver and the difference of the vehicle with an ideal trajectory. The amplitude of the steering feedbacks would increase with the increase of the trajectory difference, ensuring the linearity of the increase of the steering feedbacks. As a result, the driver would be constantly stimulated, avoiding the overstimulation and ensuring safe stimulation of the driver. Moreover, these stimulations are effective to stimulate impaired driving and driver presenting normal conditions. Indeed, the benefit of applying haptic steering guidance feedbacks to the steering wheel can be easily understood as these stimulations are awaking the neuromuscular mechanism of the driver. Furthermore, driver presenting normal neuromuscular condition would also benefit from the application of haptic steering guidance feedbacks to the steering wheel since they interact with the assistance system, as the best of their capacities. They can also benefit from the application of the haptic steering guidance feedbacks by maximizing their interactions with the assistance system to optimize the influence of steering haptic feedbacks.

In most situations, the application of haptic feedbacks on the steering wheel appears to be beneficial to influence the condition of the driver and is consequently selected in this dissertation to influence the condition of the driver.

3.2.2. The intentions of the drivers in the design of haptic steering guidance system

In order to optimize the influence of haptic steering guidance application on the steering wheel, the intention, which are often dependent on the condition of the driver, must be known. Indeed, conflict between the trajectory decided by the driver and the ideal trajectory computed by the assistance system may occurs if the intentions of the driver are unknown. This case occurs, for most of cases, for driver presenting normal neuromuscular conditions since they are aware of the road environment and conscious of the driving risks. They choose consequently the trajectory of the vehicle that seems appropriate to them for ensuring their safety and the safety of the passengers.

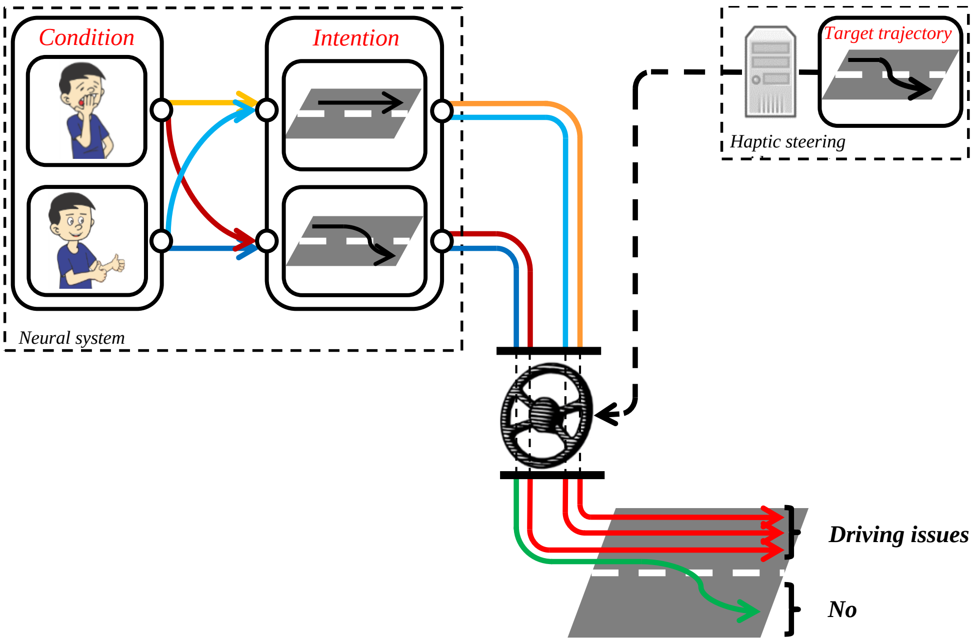


Figure 14. Representation of possible interferences between the assistance system and the driver.

An illustration that presents the possible conflict between the intentions of the driver depending on his or her condition and the steering assistance system can be observed in the Figure 14. If the driver wants to remain in the current lane, independently from his or her physical condition, but the steering assistance system is planning a lane change, it results in a conflict between the driver and the steering decision system. These possible issues are represented with the blue and orange lines. Moreover, if the driver wants to perform a lane change but his or her condition is abnormal, because of impaired driving, even if the steering assistance system is helping the driver to perform the lane change, the exhibited steering operation might be hazardous if the steering assistance system does not consider the condition of the driver. This situation is represented by the red line in the Figure 14. Regarding the different scenarios, it is important to consider the condition of the drivers and their driving intention for avoiding conflict with the haptic assistance system.

Because of the intrusive nature of the sensors that can acquire the intention of the driver, it has been difficult to develop a viable assistance system that considers the physiological data of the driver. Indeed, the intentions of the drivers can be acquired through scapula sensors, for example, which retrieve the EEG wavelet at the surface of the scalp. The intentions of the driver can also be acquired using sensors, attached to the skin, that measure the electric activity of muscles, so-called EMG. The EMG is a method for evaluating the electrical activity produced by skeletal muscles. However, these methods are not viable for commercial applications.

Consequently, mechanical arm admittance appears again to fulfil the requirement of the non-intrusion of the sensor and permits to investigate the condition of the driver, which confirms the relevance of the use of this metric in this dissertation. A schematic figure that represents the different interactions of the driver with the road and the assistance system, and the influence of the condition of the drive on the decision of the assistance system, is presented in following.

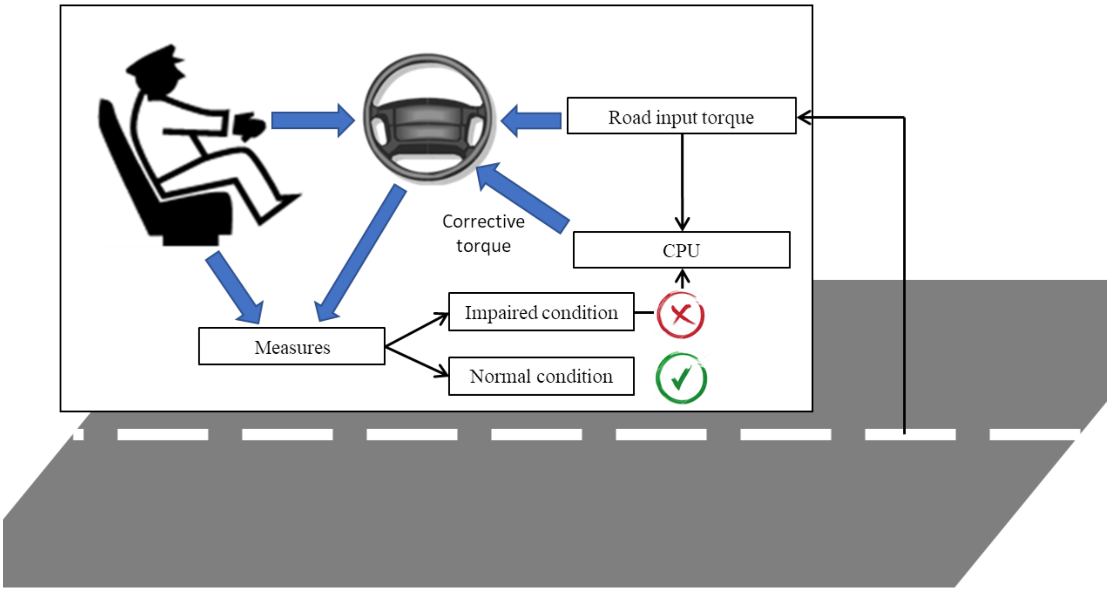


Figure 15. Principle of steering corrections.

It describes a human in the decision system loop where the driving decision of the driver is considered by the acquisition of suitable variables that indicate the NMS of the driver. Consequently, the condition of the driver must be considered when providing steering torque.

Chapter 4

Experiments

4. *Experiments*

The experiments in this dissertation were approved by the Ethical Judgment Committee of The University of Tokyo, ID number 13-25, registered on 30 May 2013.

4.1. Driving simulator, participants, and driver posture

Experiments in this dissertation were performed using a high fidelity driving simulator composed of a 6-degrees-of-freedom motion platform, with a scenario projection on three screens for a 140 degrees of vision angle. The steering system is composed of an electric power steering system of an actual vehicle, and the motor of the electric power steering system worked as the actuator to emulate road feedback including self-aligning torque. The actuator of the steering system can render a range of dynamics and exert a maximum torque of 10 Nm. The steering system was connected to the host computers and the entire system was synchronized at 120 Hz.

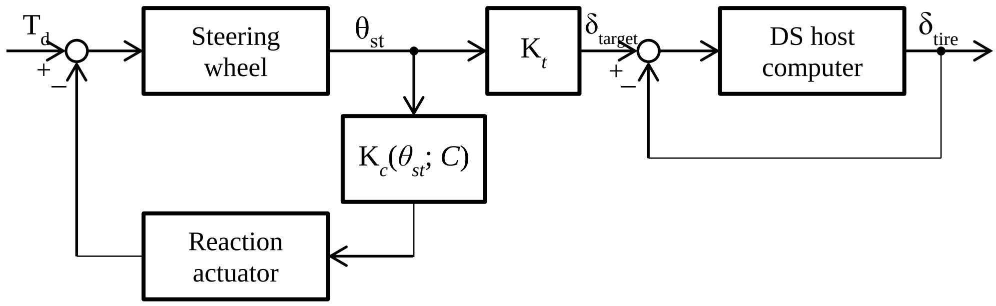


Figure 16. Representation of the driving simulator interactions between the steering wheel, the motion platform and the control system.

In the Figure 16, T_d represents the driver torque, θ_{st} represents the steering wheel angle, C the road characteristics of the road, δ_{target} represents the target and δ_{tire} the front tire angle. These variables are considered when computing the output tire angle of the vehicle that rules the trajectory of the vehicle. The driving simulator of Nakano laboratory, was used for experiments and the characteristics of the motion platform can be observed in Table 2.

Table 2. Characteristics of the motion platform used during the experiment.

		Range	Speed	Acceleration
Position	Longitudinal	-200mm ~ +180mm	300mm/s	5 m.s^{-2}
	Lateral	±190mm	300mm/s	5 m.s^{-2}
	Vertical	-190mm ~ +230mm	300mm/s	5 m.s^{-2}
Angle	Roll angle	±12deg	20deg/s	-
	Pitch angle	±12deg	20deg/s	-
	Yaw angle	±11deg	20deg/s	-

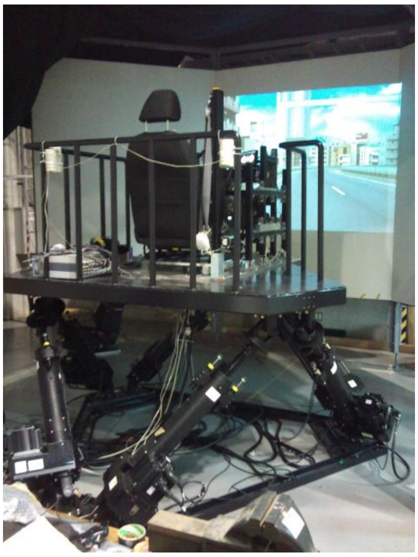


Figure 17. Photography of the driving simulator.

As the posture of the driver holding a steering wheel can affect the quality of the driving, the participants of the experiments were asked to adopt their most comfortable posture. According to the literature, the seat of the driver must be designed to fit the contours of human body for enhancing the driving comfort [42]. Indeed, a deficient seat posture could affect the steering wheel performances since the driver do not get used to an improper driving posture. This point has been addressed in the past by the diction of certain rules by the society of automobile engineers (SAE) and Automotive Industry Standards (AIS) has configured the range of dimensions for car seat and spatial configuration [43]. Since most seats are respecting the rules dictated in this protocol, the posture adopted by the driver during the driving experiment are sufficient to perform natural steering motions. Furthermore, participants of the different experiment were asked to fasten their seatbelt, which has two outcomes concerning the maintenance of the driving posture. The first outcome of fastening a seatbelt in a driving simulator is to reproduce similar driving condition to a car. It simulates real-driving conditions, of which drivers are used to in order to make the experiment realistic. Moreover, fastening a seatbelt permit to maintain the driver close to the back-rest angle, which was proved to be efficient to improve the comfort while driving [44].

Moreover, the arm configuration while driving also plays a role in the steering performances. As presented in the Figure 20, the muscles playing a role in the motion of the steering are the front deltoid, the pectoralis major, the triceps long head and the biceps brachii, which their levels of activation can change the dynamics of the joints of the arm. which play a role in the control of the steering operations. Thus, the steering performances also depend on the joint stability of the arm and the muscle activation level, which control the accuracy of the steering motion in a normal situation or facing steering perturbations. To illustrate it, Flash et al. examined the dynamic of the arm by observing the stiffness of the different joints, linked with the evaluation of the level of activation of muscles involved in the arm motions [45]. Their method consisted in recording EMG signals from shoulder, elbow and two joint muscles to observe the activation of these. They found that there is a substantial dependency of the joint stiffness on the arm configuration, which demonstrates that the arm configuration affects the steering performances. Moreover, it was demonstrated by Pick et al. that high levels of co-contraction were used to allow high-frequency steering inputs to be generated, highlighting the variation of the arm characteristics depending on the steering frequency [46]. Furthermore, De Vlugt et al. indicated that reflexive feedbacks, that are present at lower frequencies largely contribute to the amplitude of mechanical arm admittance during multi-joint posture maintenance, also highlighting the variation of the arm characteristics depending on the steering frequency [34]. These examples prove that the arm posture and driving posture are important in the steering operations performances.

In the experiment of this dissertation, in order to mitigate the effect of driving and arm posture variance among drivers, participants were asked to adopt the most comfortable seating position, which acts as a normalization method of the posture while driving. As a result, the degradation of the arm posture caused by impaired condition is consistent for all the participants of the experiment, which relates that the results obtained are similar for all the subjects.

Moreover, males participants were preferred for experiments because of the possible occurrence of motion sickness among female population. Motion sickness has been described by Bles et al. who established that drivers can feel dizziness, auditory troubles, headaches, and abdominal discomfort after a driving simulation because of de-synchronization between visual and vestibular systems [47]. Kelly, Lassacher and Shipstead showed that a possible 10% of participants were affected by these symptoms, especially females [48].

4.2. Experimental method for the estimation of mechanical arm admittance in real-time

In order to estimate mechanical arm admittance, the commonly used method is to apply steering perturbations and capture the steering reactions of the driver. The design of the steering perturbations is crucial since it stimulates the driver via the reactions of the arms while handling the steering wheel. Indeed, to perform the frequency analysis of mechanical arm admittance, the frequencies of the steering perturbations should be similar to the frequencies at which mechanical arm admittance is estimated. It has been emitted by Schouten et al. that ideal steering perturbation characteristics for an optimal estimation of the characteristics of mechanical arm admittance are

- Persistently exciting;
- Long enough to obtain satisfactory frequency content, but short enough to shorten the measurement time, not to induce fatigue;
- A multi-sine signals which contain a limited number of stimulated frequencies, which are logarithmically spaced
- Moreover, Katzourakis et al. detailed that steering perturbation frequencies under 0.5 Hz are difficult to reproduce for driving simulator operators, which may lead to data distortion that shows low coherence [49].

As a result, the chosen frequencies that aim to stimulate the FRF of the arm of the driver in order to evaluate mechanical arm admittance should be equal or higher than 0.5 Hz for avoiding misinterpretation about the amplitude of mechanical arm admittance.

A multi-sine signal is a combination of sinus signals that aim to stimulate different frequencies according to previously cited statement. The perturbation torque applied to the steering wheel should resemble to

$$T_{pert} = k_0 \cdot \sin(f_0 \cdot t) + k_1 \cdot \sin(f_1 \cdot t) + ... + k_n \cdot \sin(f_n \cdot t), \tag{10}$$

where k indexed n is the gain of the sinus that stimulate the frequency f indexed n. n corresponds to the number of stimulated frequencies. As the dominant human power lies in a frequency domain ranging 0.5-5 Hz, the number n should not be too high to distinguish the frequency effect of amplitude of mechanical arm admittance. Moreover, the gains k indexed n should be similar, at the exception of special investigation.

To test the points mentioned above, nine different logarithmically spaced frequencies (bullet 3 of signal requirements) were included in a perturbation signal, ranging from 0.5 Hz to 5 Hz (bullet 4 of signal requirements). The duration of the perturbation signal was set to 60 seconds (first and second of signal requirements). Furthermore, the disturbance signal was linearly phased to full power within 3 seconds, and faded out within 3 seconds, in order to gradually stimulate the drivers at the beginning and at the end of the steering task. The maximum amplitude threshold of the steering perturbation signal was set to 1 Nm, in order to maintain highly coherent data. The time history of the created steering perturbation signal can be observed in following.

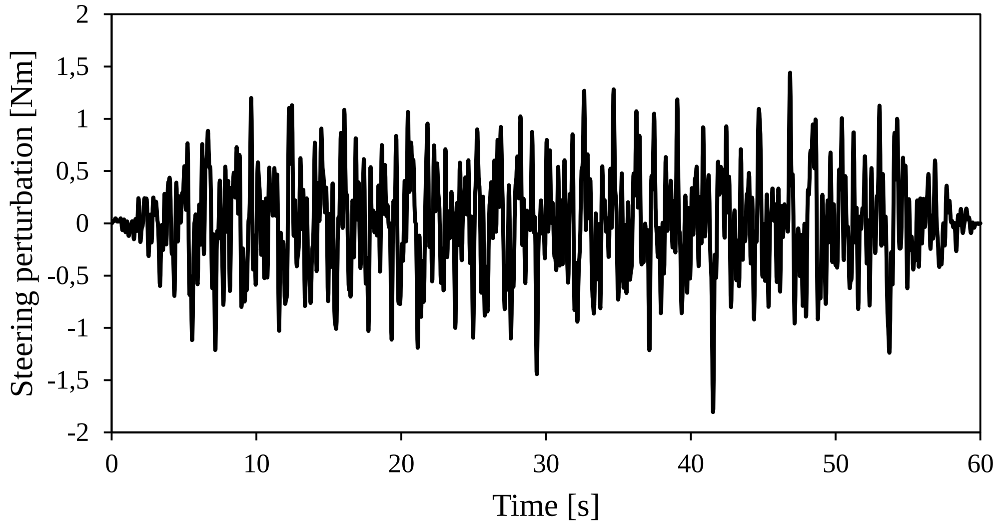


Figure 18. Example of a steering perturbation signal used for the estimation of mechanical arm admittance.

To test the repartition of the stimulated frequencies, the time domain signal of the created steering perturbation signal was transformed in the frequency domain using a fast Fourier Transform (FFT). A FFT is an algorithm that samples a signal over a period of time (or space) and divides it into its frequency components. These components are single sinusoidal oscillations at distinct frequencies, with their own amplitude and phase for each. Fourier analysis converts a signal from its original domain to a representation in the frequency domain and vice versa, which makes it relevant in this situation to analyse the frequency characteristics of the perturbation signal. The FFT of the steering perturbation signal is presented in following.

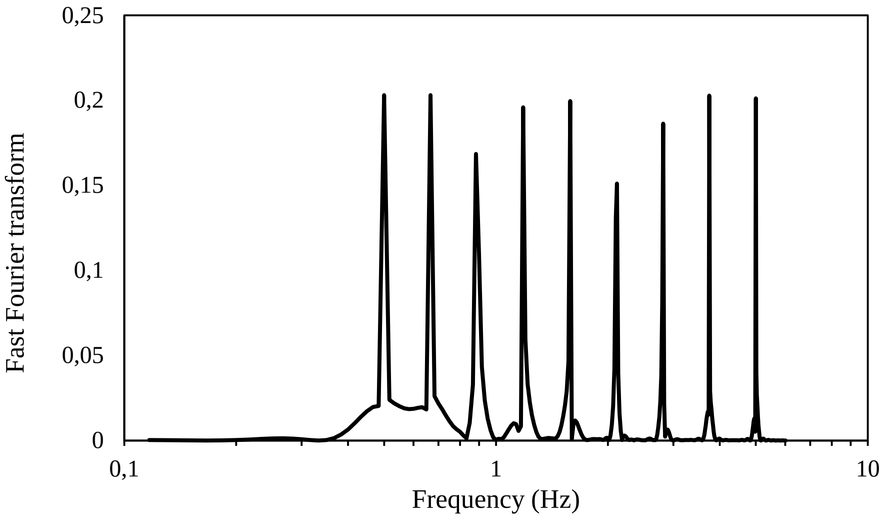


Figure 19. Stimulated frequencies by the steering perturbation signal.

It can be observed in the Figure 19 that the amplitudes of the FFT harmonics are similar and occur at regular logarithmic intervals. This analysis was performed to ensure the quality of the steering perturbation signals, used in this study to estimate mechanical arm admittance.

4.2.1. A direct method for estimating mechanical arm admittance without steering perturbations

The inconvenience when using mechanical arm admittance as an estimation of the condition of the driver is that it requires the driver to be perturbed by steering perturbation signals. The FRF of the arm is analysed via the estimation of mechanical arm admittance and a statement on the condition of the driver can be done.

However, this can be a problem for vehicle applications since the application of steering perturbations is not recommended to ensure the safety of the driver. As a result, an alternative method for finding the amplitude of mechanical arm admittance is required.

For finding a relevant method to acquire the condition of the driver, the role of the upper limb in the steering operation is required as arms plays an important role in producing steering torque to operate manoeuvres of the vehicle.

Right arm and left arm are supplementary for generating torque on a steering wheel and same muscles of each arm are involved in generating positive and alternatively negative torque. Arm motions while rotating steering wheel involve muscles of forearm, upper part of the arm and back's muscles.

The main muscles that play a role in the steering wheel operation are:

- mid and front deltoid
- sternal portion of the pectoralis major
- triceps long head
- biceps brachii

In the Figure 20, the placement of the previously cited muscles is indicated.

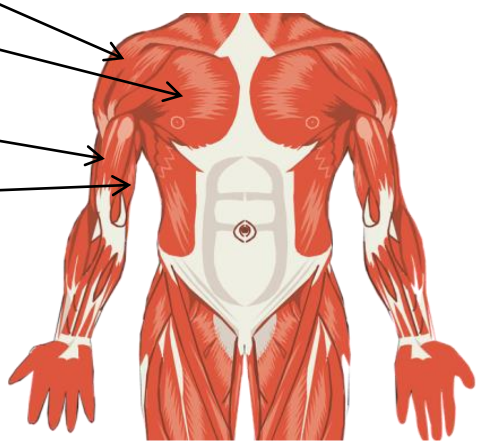


Figure 20. Muscles playing a role in steering operations.

These muscles are involved in steering wheel rotation motion, while steering wheel maintaining is ensured by hands as grip force represents the ability of driver to maintain the contact with the steering wheel without sliding. Zatsiorsky investigated in the apparent stiffness of the human arm during posture maintenance and highlighted the importance of muscle activation of the arm while performing steering operations, highlighting the role of the hand [50]. Indeed, the hand grip is linked with the capacity of adherence of the hand with the steering wheel in case of steering perturbations. The amplitude of the grip force applied to the steering wheel is consistent with the capacity to resist to steering perturbation and represents the intentions of the driver since drivers with a high level of attention present an accurate control of the steering wheel. In case of relaxed driving behaviour, the driver might not be able to counter the negative influence of steering perturbations or even to provide accurate input torque to follow the trajectory of the road.

Moreover, Flash and Mussa-Ivaldi suggested that global arm stiffness changes, which also include hand, are distributed over all arm muscles consistently [51]. Muscles spanning may follow similar activation pattern when hand posture is shifted in the workspace (steering wheel is considered as the workspace in our case). Taken together, it indicates that hand stiffness and arm stiffness are linked in a uniform way. Thus, equivalence between of arm stiffness and grip pressure can be assumed.

Furthermore, it was presented in the section 3.1.2 that mechanical arm admittance model that uses bio-mechanical coefficients include interactions of the hand properties with the equation of mechanical arm admittance. As a result, it was decided to investigate the relationship between grip pressure and mechanical arm admittance, aiming at suppressing the steering perturbation requirement for the estimation of mechanical arm admittance.

In the following paragraph, a description of the experimental procedure is done to permit the investigation of a direct method for estimating mechanical arm admittance without steering perturbations. The driving scenario consisted in a straight road on which drivers had to follow an indicated trajectory, the middle of the road, while steering perturbations were applied on the steering wheel in order to activate the grip mechanism and estimate mechanical arm admittance. The steering perturbations consist in a series of sinusoidal-shaped steering perturbations, which stimulate different frequencies. For given amplitude, the driver experienced the series of steering perturbations lasting 20 seconds each. Participants were instructed to firmly grab the steering wheel in a 'ten-to-two' position while wearing grip sensors gloves. Prior to the recording, participants performed the scenario once for training purposes. Participants experienced different amplitudes of steering perturbation. To simplify the driving tasks, participants only had to steer, and the driving speed was fixed to 40 km/h for better comparison of steering activity. The recorded driving variables were the steering wheel angle θ, the driver torque d and the perturbation torque t for the estimation of mechanical arm admittance and the driving performances, and the grip pressure P_{grip} applied on the steering wheel. In the following paragraph, a description of the participants details of the experiment described in this section is proposed.

The participants involved were all volunteers. A total of 10 drivers aged 22–29 years (mean age 24 ± 2.05) performed the experiment. On average, they had held a Japanese driver license for 3.9 years and drive 610 km a year in average. All participants were asked to sign a cooperation agreement form after being informed of the experimental details. The personal information were collected and protected according to participant protection rules. In the following paragraph, a description of the methodology employed in this experiment is proposed.

In order to investigate the relationship between mechanical arm admittance and grip pressure in the frequency domain, the measurement from the driving simulator were made at 120 Hz. Grip pressure was also recorded at 120 Hz using Tekscan grip sensors. They consist in thin sensors that were built into a glove as it can be observed in the Figure 21.

Figure 21. Tekscan grip sensors used for the measurement of the grip pressure.

The contribution of both hands in the steering operations was considered in the analysis. The evaluation of the grip pressure was performed using the sum of force applied on the gloves as

$$P_{grip} = \sum_{i}^{n} F_i \cdot a_i , \quad (11)$$

where F_i is the force applied on sensing cell a_i indexed by i and n the number of activated sensing cells. Since mechanical arm admittance is computed in the frequency domain, the fast Fourier transform (FFT) of the grip pressure was computed. Because of the presence of noise in the grip pressure FFT, the averaging of three adjacent points for the different steering perturbation frequencies was computed. Then, the amplitude of the FFT of the grip pressure and the gain of mechanical arm admittance were linked for the different steering perturbation frequencies. This set of data was used to investigate the tendency of the investigated relationship. Then, tendency curves were added to the data set of which their characteristic equation was designed to fit a power function as

$$y = a \cdot x^{b}, \quad (12)$$

where y is the mechanical arm admittance gain, x is the FFT of grip pressure, a and b are the characteristic coefficients of the equation that represent the tendency curve, and R^2 the coefficient of determination of the equation, which indicates quality of the estimation.
The results of this section are presented in section 5.1.1. They are discussed, and a conclusion is made on the proposed method to estimate mechanical arm admittance without steering perturbations.

4.2.2. The investigation of the amplitude scale of mechanical arm admittance for real-time application

Previous studies could express the driver NMS by comparing mechanical arm admittance gains during a tensed driving trial and a relax driving trial. For real-time applications, such comparison cannot be performed, as the relax/tensed NMS baseline is unknown. As a result, a critical point of the real-time monitoring of driver using mechanical arm admittance is to know for each participant the NMS state associated to the amplitude mechanical arm admittance. In the following paragraph, a description of the experimental procedure is done to permit the investigation of the scale in amplitude of mechanical arm admittance for real-time application.

The real-time monitoring of drivers using mechanical arm admittance as an indicator of their intentions necessitates the knowledge of the scale of the amplitude of mechanical arm admittance that driver can present. In order to investigate the amplitude range of mechanical arm admittance, an experiment, in which we tested the steering reaction of driver for various amplitudes of steering perturbation, was performed. In the following paragraph, a description of the participants details of the experiment described in this section is proposed.

The participants involved were all volunteers. A total of 4 drivers (mean age 21.3 ± 1.26) performed the experiment. On average, they had held a Japanese driver license for 3.3 years. All participants were asked to sign a cooperation agreement form after being informed of the experimental details. The personal information were collected and protected according to participant protection rules. In the following paragraph, a description of the methodology employed in this experiment is proposed.

In this study, mechanical arm admittance was estimated using the equations presented in the section 3.1.2. The scenario consisted in a straight road on which the participants must follow a straight trajectory. Steering perturbations of (0.5, 1, 1.5, 2, 2.5 and 3.5) Nm amplitudes were applied and mechanical arm admittance was estimated for these different amplitudes of steering perturbations. Finally, the variations in mechanical arm admittance was investigated for easily controllable steering perturbation amplitude (0.5 Nm) to difficulty controllable steering perturbation amplitude (3.5 Nm). In order to review the statistical repartition of amplitude of mechanical arm admittance between the minimum and maximum values, the quartile computation is performed. The first quartile (Q1) is defined as the middle number between the smallest number and the median of the data set. The second quartile (Q2) is the median of the data. The third quartile (Q3) is the middle value between the median and the highest value of the data set.

– Q1 (first quartile): splits off the lowest 25% of data from the highest 75%
– Q2 (median): cuts data set in half
– Q3 (third quartile): splits off the highest 25% of data from the lowest 75%

These statistical indicators are used in this section to estimate the repartition of the amplitude of mechanical arm admittance between the minimum and maximum amplitude.
The results of this section are presented in section 5.1.2. They are discussed, and a conclusion is made on the possible range of amplitude of mechanical arm admittance and its repartition.

4.3. The influence of impaired neuromuscular condition on mechanical arm admittance

As the characteristics of mechanical arm admittance can be estimated in real-time, the neuromuscular condition of the driver can be known. However, impaired condition while driving affects the neuromuscular condition of the driver, and its effect on mechanical arm admittance should be consequently investigated to detect an impaired condition.

4.3.1. The influence of drowsiness on MAA

Drowsiness is defined as a state in which a person abnormally feels asleep at an inappropriate time during the day. It is an intermediate state between alert wakefulness and sleep, to be distinguished from fatigue and expressing a fluctuating state of reduced awareness and impaired psychomotor performance [52]. Falling asleep while driving, even if it lasts a short instant, substantially increases the risk of accident. In most cases, drivers are not able to react and accidents occur. Many parameters that can be physiological as well as behavioural and situational influence driver drowsiness. They include driver age and experience, cumulative sleep debt, presence of a sleep disorder, perturbation of circadian rhythm, or increase in duration of driving tasks [53][54][55]. People deprived of sleep are less likely to be physically active, and lack of sleep enforces the body to consume energy to equilibrate metabolic transfer. Moreover, food habits play an important role in avoiding drowsiness [56][57].

Numerous measures and techniques have been employed to measure driver drowsiness. Most of them involve self-evaluation assessment based on questionnaires, psychomotor tests based on reaction time and focus, variations in driving performance, measurement of physiological variables such as EEG or EMG, and ocular and facial variables evaluation.

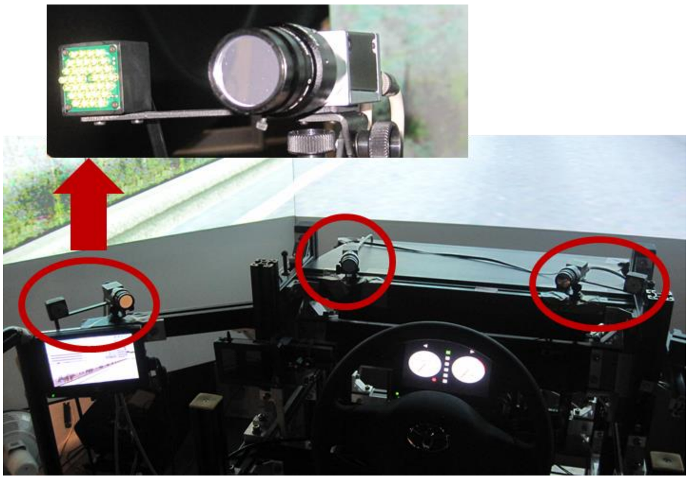


Figure 22. SmartEye set of cameras used in this study to measure the motions of the eyelid of participants.

Many studies have concluded that eye tracking is a valid measure of drowsiness evaluation, and provides various types of information that can reveal the physiological state of subjects [10]. Recent progress in machine vision research and advances in computer hardware technologies have made possible the measurement of eyelid movements accurately.

As drowsiness is impairing the condition of the driver, effect on the neuromuscular condition of the driver should be observed. The original objective of this study is then an investigation about the effects of drowsiness on mechanical arm admittance. In the following paragraph, a description of the experimental procedure is done to permit the investigation of the influence of drowsiness on mechanical arm admittance, which permits to know its effects on the neuromuscular condition of the driver.

The experiment was scheduled on two different days. The first day, which corresponds to the first stage of the experiment, corresponded to a drowsy state. The purpose of the first stage was to produce drowsiness by multiplying drowsiness factors. Participants of the experiment were instructed to shorten their sleep during the night preceding the experiment to 5 hours, skip breakfast on the experiment day, avoid drinking caffeine-based beverages on the experiment day, and consume a high quantity of fast food for their lunch. Furthermore, experiments were vehicleried out at 2 O'clock in the afternoon, where a drowsiness peak often appears because of digestion. A monotonous scenario that lasts 24 minutes was built and mechanical arm admittance was estimated at the end of the scenario performing. Indeed, researchers have inferred that prolonged driving in a monotonous environment stimulates drowsiness. It has been observed that most participants show drowsiness within 20 to 25 minutes of driving [58]. In order to monitor the evolution of drowsiness of drivers during the first stage, participants were asked to rate their drowsiness level using Karolinska Sleepiness Scale grades each three minute. Furthermore, the evolution of the eyelid motion was analysed to ensure that the drivers were drowsy at the time of the estimation of mechanical arm admittance.

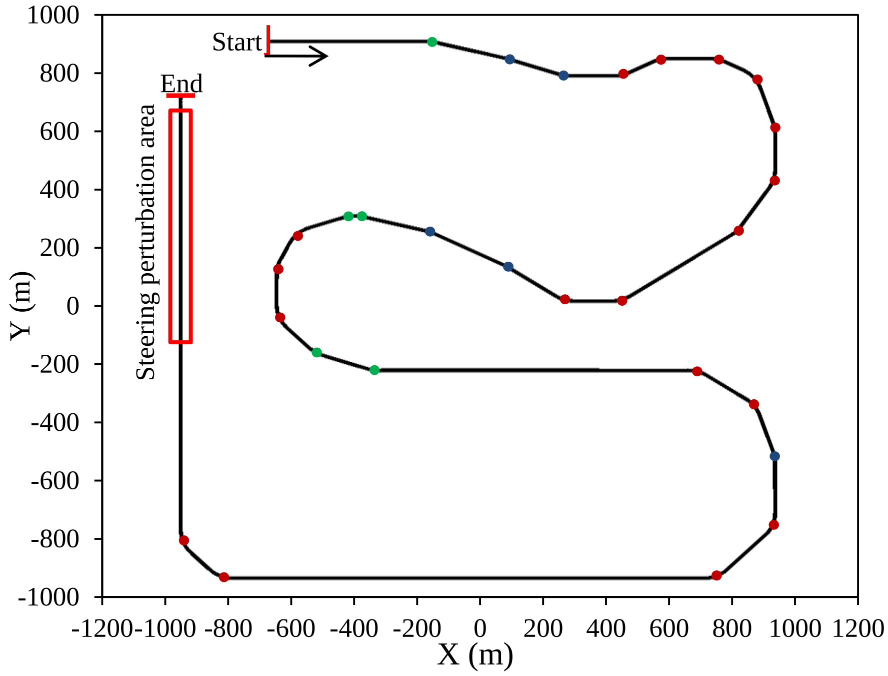


Figure 23. Design of the experimental scenario. Red dots correspond to 150 meters radius curves, green to 300 meters radius curves and blue to 400 meters radius curves.

Participants were asked to minimize the influence of steering perturbations by maintaining a stable trajectory of the vehicle. The purpose of the second day of the experiment, which corresponds to the second stage of the experiment, was to evaluate mechanical arm admittance for alert drivers. The driving task performed by participants was limited to steering perturbations area since drowsiness inducement was not desired. Alert participants were asked to minimize the influence of steering perturbations by maintaining a stable trajectory of the vehicle. Finally, the difference in amplitude of mechanical arm admittance was estimated between drowsy and alert drivers. In the following paragraph, a description of the participants details of the experiment described in this section is proposed.

The participants involved were all volunteers. A total of 10 participants aged 21–25 years (mean age 23.4 ± 1.4 years) performed the experiment. On average, they had held a Japanese driver license for 4.3 years, and drive 1280 km each year on average. All participants were asked to sign a cooperation agreement form after being informed of the experimental details. The personal information were collected and protected according to participant protection rules. In the following paragraph, a description of the methodology employed in this experiment is proposed.

In this study, mechanical arm admittance was estimated using the equations presented in the section 3.1.2. As stated before, situational parameters can modify the level of drowsiness. Driver drowsiness mainly depends on the quality of the last sleep, the circadian rhythm and the duration of the driving task. Observational studies have shown that drowsiness occurs late at night (0:00 am – 7:00 am) or during mid-afternoon (2:00 pm – 4:00 pm), often occurs when the driver is alone in the car and occurs on a high-speed roadway [55].

The drowsiness level of participants was evaluated by measurement of the values of blink duration and the amplitude to velocity ratio of eyelid movements. A set of three cameras designed by Smart Eye AB (Gothenburg, Sweden) was used for eye variables acquisition. The disposition of the Smart Eye device was arranged in order to provide a 140 degrees continuous recognition field of view, similar to the field of view of the scenario. It allows participants to maintain a natural driving behaviour during the experiment.

The scores of drowsiness self-evaluation questionnaire by two distinct questionnaires were used for assessing drowsiness level of participants. The Karolinska Sleepiness Scale (KSS) was used to capture the real-time driver experience of sleepiness. This scale is graded across nine levels and goes from 1 = very alert to 9 = very sleepy, a great effort to keep alert, fighting to sleep. Participants are asked to state their level of sleepiness at regular time intervals and the evolution of drowsiness can be observed. Moreover, the Time of Day Sleepiness Scale (ToDSS) test performed beforehand and was used as an estimation of the sleepiness background of the participants [58]. The ToDSS consists of eight items to enable subjective assessment of sleepiness across the day. For each item, participants are asked to rate sleepiness across 4 levels from 0 = very alert to 3 = very sleepy at morning, afternoon and evening times. The addition of these scores gives an estimation of the sleepiness background of subject across the day from 0 to 24, in which 0 meaning no possibility to fall asleep and 24 meaning a high probability to fall asleep.
The results of this section are presented in section 5.2.1. They are discussed, and a conclusion is made on the impact of drowsiness on mechanical arm admittance.

4.3.2. The influence of cognitive distraction on MAA

In the late 90's, creation of viable ADAS drastically increased road safety especially via the incorporation of devices such as antilock braking system, collision mitigating braking systems or electronic stability control. Furthermore, IVIS were improved to provide drivers useful information or ameliorating their driving quality. Thus, nowadays car technologies are strongly developed, and many information devices are embedded in vehicles to provide accurate information to the driver on his or her environment. As a consequence, drivers are requested to check many signals on the dashboard which can include GPS, parking aid or blind spot information system. However, the paradox of incorporating many IVIS devices in a car lies in the focus that the driver directs to those devices [59]. Most of times, it entails an increase in the mental workload on the driver which is likely to create fatal interferences to the driving attention.

Distracted driving, not to be confused with driver inattention, is any activity that could divert driver's attention away from his or her primary task. There are four main types of distraction in driving: visual distraction (taking eyes off the road), manual distraction (taking hands off the steering wheel), auditory distraction (e.g. listening to radio), and cognitive distraction (taking mind from driving). These types of distraction can be separated into two categories, which are physical distraction (biomechanical) and cognitive distraction (visual, auditory, and cognitive). The physical distraction relates to the obstruction of the driver motion for achieving safe and stable control of the trajectory of the vehicle while cognitive distraction relates to the competition between the driving task and a secondary task that induce an increase of the mental workload.

If such distraction happens while driving, focus will be drawn to these secondary tasks instead of being allocated to the driving and the driver's safety will be at risk. Each type of distraction act differently on the control of the vehicle by the driver since the areas of the brain concerned varies. It was demonstrated in the thesis of Sterkenburg that the impact of physical distraction and cognitive distraction does not results in a difference of car accidents, expressing that the impact of both categories of distraction is similar [60]. However, in the particular case of mobile phones, a study of the literature by Horrey et al., highlighted that driver's reaction times are significantly increased by phone conversation [61]. As a result, the impact of specific distraction on the driver are diverse and further investigation are required. In this dissertation, we decided to investigate the impact of cognitive distraction on the neuromuscular condition of the driver. In order to know the influence on distraction on the NMS of the driver, its influence on the amplitude of mechanical arm admittance is investigated. In the following paragraph, a description of the experimental procedure is done to permit the investigation of impact of cognitive distraction on mechanical arm admittance, which permits to know its effects on the neuromuscular condition of the driver.

The experiment was scheduled on two different days. The first day, participants were requested to perform the scenario with cognitive distraction. The second day, participants were requested to perform the scenario without cognitive distraction. The cognitive distraction was induced using a Paced Auditory Serial Addition Test (PASAT). This test consists of a series of mathematic additions which its target is to assess capacity, rate of information processing, sustained and divided attention. Proceeding of the test consists in announcement of succeeding digits. At each digit change, subjects must sum the current and the previous announced digit as shown on the Figure 24. The aim of this step is to increase the mental workload on the driver to produce driving mistakes. The NORMAL scenario and PASAT scenario were repeated 3 times each for improving the estimation of mechanical arm admittance and enhance the detection of the cognitive distraction of the driver by observing the variations in amplitude of mechanical arm admittance.

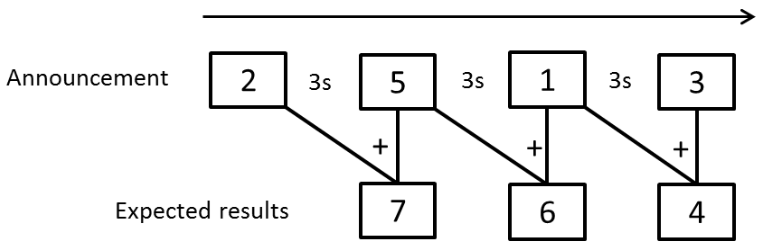


Figure 24. PASAT test principle.

In the following paragraph, a description of the participants details of the experiment described in this section is proposed.

The participants involved were all volunteers. A total of 10 participants aged 22 - 49 years (mean age 35.2 ± 8.61 years) performed the experiment. On average, they had held a Japanese driver license for 10.8 years. All participants were asked to sign a cooperation agreement form after being informed of the experimental details. The personal information were collected and protected according to participant protection rules. In the following paragraph, a description of the methodology employed in this experiment is proposed.

In this study, mechanical arm admittance was estimated using the equations presented in the section 3.1.2. The amplitudes of mechanical arm admittance of the stage with PASAT were compared with the amplitudes of mechanical arm admittance of the stage without cognitive distraction. The PASAT stage was performed at first in order to avoid the driver to get used to the shape of the curvature. Performing the NORMAL stage in second does not cause experimental issues since the participants are supposed to react at the best of their capacities to the steering perturbations. The driver experienced the steering perturbation for a period of 2 minutes on a curved road, which aims to estimate mechanical arm admittance in a condition where the driver has to perform steering operations to follow the trajectory of the road.

The results of this section are presented in section 5.2.2. They are discussed, and a conclusion is made on the impact of cognitive distraction on mechanical arm admittance.

4.4. Influence of haptic steering guidance control on mechanical arm admittance

If an impaired condition of the driver is detected by variations on mechanical arm admittance, decision to prevent car accident should be taken. However, a continuous enhancement of the condition of the driver is considered in this dissertation to prevent the degradation of the condition of the driver. In order to achieve it, haptic steering guidance is considered.

4.4.1. The design of haptic steering guidance to enhance the condition of the driver

Haptic steering guidance control applied to the steering wheel is an assistance method of human-automation interaction that allows both the human and the automation to exert forces on steering wheel, of which the output steering angle remains the direct input to the haptic algorithm, creating a close-loop control of the steering wheel. Haptic shared control has been developed to implement the smooth transfer of control authority [19][20][62]. Although various studies have investigated the implications of human behaviour in human/haptic interaction, the intrinsic influence of haptic steering guidance design on driver has yet to be determined. Reliable indicators of driver intentions are challenging to establish [63][64], and confusion in the acceptance of the haptic shared control can lead to substantial errors. In the following paragraph, a description of the experimental procedure is done to permit the investigation of the optimal design of haptic steering guidance to influence the neuromuscular condition of the driver.

In this study, we propose to investigate the effects of different design of haptic steering guidance control on mechanical arm admittance. The driving scenario consisted of a straight road on which drivers had to follow an indicated trajectory (middle of the road) while steering perturbations were applied to the steering wheel. They were instructed to firmly grab the steering wheel in a “ten-to-two” position. Different designs of haptic steering guidance were used to help the drivers to diminish the influence of perturbation and assist them in trajectory following. Participants also experienced different amplitudes of steering perturbations. To simplify the driving tasks, participants only had to steer, and the driving speed was fixed to 40 km/h for better comparison of steering activity. Three amplitudes of the multisine signals, 0.5 Nm, 1 Nm and 2 Nm, were used to investigate the difference in driver response depending on steering perturbation amplitude and haptic steering guidance gain. In total, participants performed $3 \times 8 = 24$ trials (three steering perturbation amplitudes * seven haptic steering guidance designs + three steering perturbation amplitudes * one trial without haptic steering guidance). The haptic steering guidance designs were ordered randomly for this experiment, but the steering perturbations were applied with an increase of amplitudes. In the following paragraph, a description of the participants details of the experiment described in this section is proposed.

The participants involved were all volunteers and were recruited from the university student population. A total of fourteen participants aged 23.7 +/− 1.9 performed the experiment. On average, the participants had held a Japanese driver’s license for 4.6 +/− 1.6 years. All participants were asked to sign a cooperation agreement form after being informed of the experimental details.

The personal information were collected and protected according to participant protection rules. In this study, the haptic steering guidance feedbacks applied to the steering wheel follow the equation (15) as

$$u = k*(a_1.e_y + a_2.\dot{e}_y + a_3.e_\theta + a_4.\dot{e}_\theta), \tag{15}$$

where u is the haptic torque applied on the steering wheel, k is the coefficient that rules the amplitude of the haptic torque, a_1 and a_2 are the coefficients that affect the lateral deviation and lateral velocity of the vehicle e_y and $\dot{e}_y$, and a_3 and a_4 are the coefficients that affect the yaw angle and yaw rate of the vehicle e_θ and $\dot{e}_\theta$. In order to investigate the influence of the design of haptic steering guidance on neuromuscular condition of drivers, a special focus on coefficients a_3 and a_4 was given, since the aim of an active steering system is to reject the influence of yaw-moment disturbances [65]. The coefficients a_1 and a_2 were chosen to provide maximum lateral velocity feedbacks. The coefficients that rule the different designs of haptic steering guidance can be observed in Table 6. Finally, seven different haptic steering guidance designs were addressed for this experiment. In order to simplify the notations, trials without haptic steering guidance are numbered 1, and the different trials with various haptic steering guidance levels are numbered from 2 to 8 as shown in the following table.

Table 6. Haptic coefficients used during the experiment that are related to Equation (3). HD means haptic design.

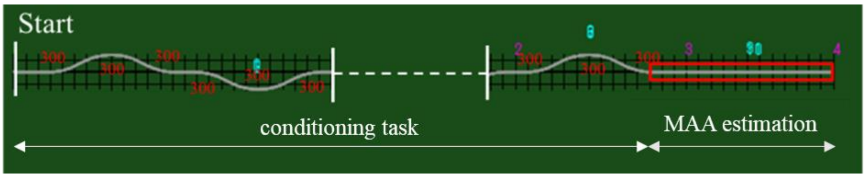
	Haptic Design No.	1	2	3	4	5	6	7	8
Haptic coefficients	k	0	1	1	1	1	1	1	1
	a_1	.	115	115	115	115	115	115	115
	a_2	.	30	30	30	30	30	30	30
	a_3	.	75	48	48	90	48	90	60
	a_4	.	1.2	30	1.2	45	15	1.2	1.2

The results of this section are presented in section 5.3.1. They are discussed, and a conclusion is made on the most efficient design of haptic steering guidance to positively influence the neuromuscular condition of the driver.

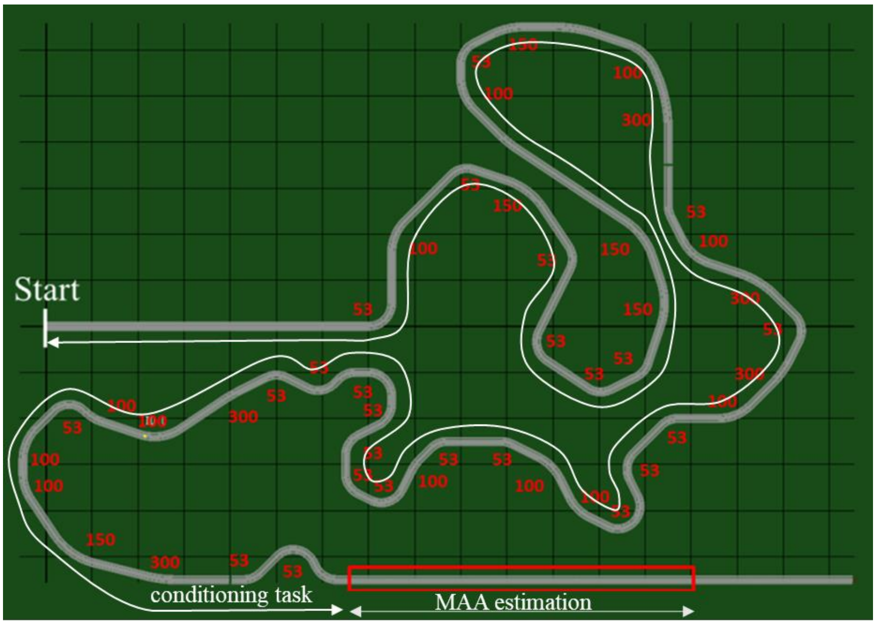
4.4.2 *Effect of application of haptic steering guidance on the neuromuscular condition of the driver*

Haptic assistance systems have insofar been evaluated in terms of safety and steering stability, but their effect on human driving behaviour has not been sufficiently explored. The optimal choice of haptic intervention depends on many factors, such as accuracy of the haptic system, traditional human factors considerations, chosen driving scenarios and defining the cognitive and neuromuscular condition of the driver. Only a few studies have evaluated neuromuscular feedback in the design of a haptic shared control system. Human have the ability to adapt their neuromuscular system to the physical environment they interact with. Because the state of the driver should be considered by the assistance system for avoiding misunderstanding about the timing of haptic steering guidance application to the steering wheel, the effect of haptic steering guidance on the state of the driver should be known. After-effects of haptic steering guidance, if they exist, should not harm drivers. The impact of haptic steering guidance application also depends on the driving difficulty since the steering operations required to perform accurate lane keeping depends on the curvature of the road, directly related to the driving difficulty. This fact should also be taken into consideration when Thus, we aim in this study to investigate the after-effects of haptic steering guidance on mechanical arm admittance. In the following paragraph, a description of the experimental procedure is done to permit the investigation of the impact of duration of application of haptic steering guidance on the neuromuscular condition of the driver.

Two scenarios were presented to the participants: a simple scenario and a complex scenario. To simplify the driving tasks, participants only had to steer, and the driving speed was fixed to 40 km/h for better comparison of steering activity. The simple scenario is composed by a succession of curves with large radius that are easy to initiate and tend to induce monotony. The complex scenario is composed by a succession of sharp turns with various radiuses with a minimum radius set as the smallest radius for safe and comfortable driving, i.e. 53 meters at 40km/h. The length of both scenarios is 8 kilometres.



a. Simple scenario.



b. Complex scenario.

Figure 25. Simple (a) and complex (b) scenarios. Red values represent radius of curves.

The aim of experiencing both scenarios is to induce a difference in steering operation occurrence that leads to difference in arm muscle activation, and possibly a difference in the effect of haptic steering guidance on mechanical arm admittance.

In the following paragraph, a description of the participants details of the experiment described in this section is proposed.

The participants involved were all volunteers. A total of 10 drivers aged 22–29 years (mean age 24 ± 2.05) performed the experiment. On average, they had held a Japanese driver license for 3.9 years and drive 610 km a year in average. All participants were asked to sign a cooperation agreement form after being informed of the experimental details. The personal information were collected and protected according to participant protection rules. In the following paragraph, a description of the methodology employed in this experiment is proposed.

In this study, mechanical arm admittance was estimated using the equations presented in the section 3.1.2. Haptic steering guidance inputs should be differentiated in accordance to driving conditions. Indeed, in easy driving conditions, drivers can easily focus on steering tasks and haptic steering guidance may not affect the neuromuscular condition of the driver due to easiness of driving task. At the opposite, difficult driving conditions are skill and focus demanding, and haptic steering guidance may provide a valuable assistance to drivers. Moreover, the duration of haptic steering guidance application during the conditioning task may also change the condition of drivers. In order to investigate the effect of the duration of haptic steering guidance on the state of the driver, the duration of application of haptic steering guidance was modulated and applied before the estimation of mechanical arm admittance. Indeed, long term haptic steering guidance and short term haptic steering guidance were applied during two distinct stages of the experiment. These trials were compared to trials without haptic steering guidance to investigate effects on the state of the driver. Regarding duration, conditioning tasks lasted twelve minutes for both levels of driving difficulty. Haptic steering guidance duration was defined as 'full' for a duration of twelve minutes, from the start to end; 'short' for a duration of five minutes, which begins after seven minutes until the end of the scenario. After twelve minutes of the conditioning task, mechanical arm admittance evaluation using steering perturbation commenced for a duration of one minute. The maximum amplitude threshold of the steering perturbation signal was set to 2 Nm, to maintain highly coherent data. Mechanical arm admittance characteristics of trials without haptic for the simple and complex scenario were used as a baseline to investigate the effect of haptic duration on mechanical arm admittance depending on the driving difficulty.
The results of this section are presented in section 5.3.2. They are discussed, and a conclusion is made on the timing of application of haptic steering guidance depending on the driving complexity.

4.5. Driving performances evaluation

In order to review the impact of the method applied to participants in this dissertation to participants of the experiment, driving metrics are computed. The Steering Reversal Rate (SRR) and the Standard Deviation of Lane Position (SDLP) are used to assess the variations of driving performance between the stage with drivers presenting impaired condition and stages with drivers presenting a normal condition. SRR has been demonstrated to be a robust indicator of driver performance and steering task difficulty [66]. The steering reversal rate is defined as the number of times the direction of the steering wheel movement is reversed over a 1-min interval through a finite angle (known as gap size). The pattern of steering reversal rate changes depending on driver state. It is acceptable to say that when drivers are focused on the steering task, they tend to make a large number of small steering corrections. Various studies that use Steering Reversal Rate usually define a fixed gap size, but there is no literature that explains how to choose these parameters and so they are usually arbitrarily chosen. In this experiment, the gap size step was set as 0.1 degrees. Moreover, Standard Deviation of Lane Position (SDLP) is a continuous measure of lane-keeping and calculated as follows

$$SDLP = \sqrt{\frac{1}{N}\sum_{n=0}^{N}(X_{\mathrm{i}} - \mu)^2}\ , \tag{16}$$

where X_{i} is the lateral position indexed i, μ is the mean value of the lateral position of the car, and N the number of data samples.

Chapter 5

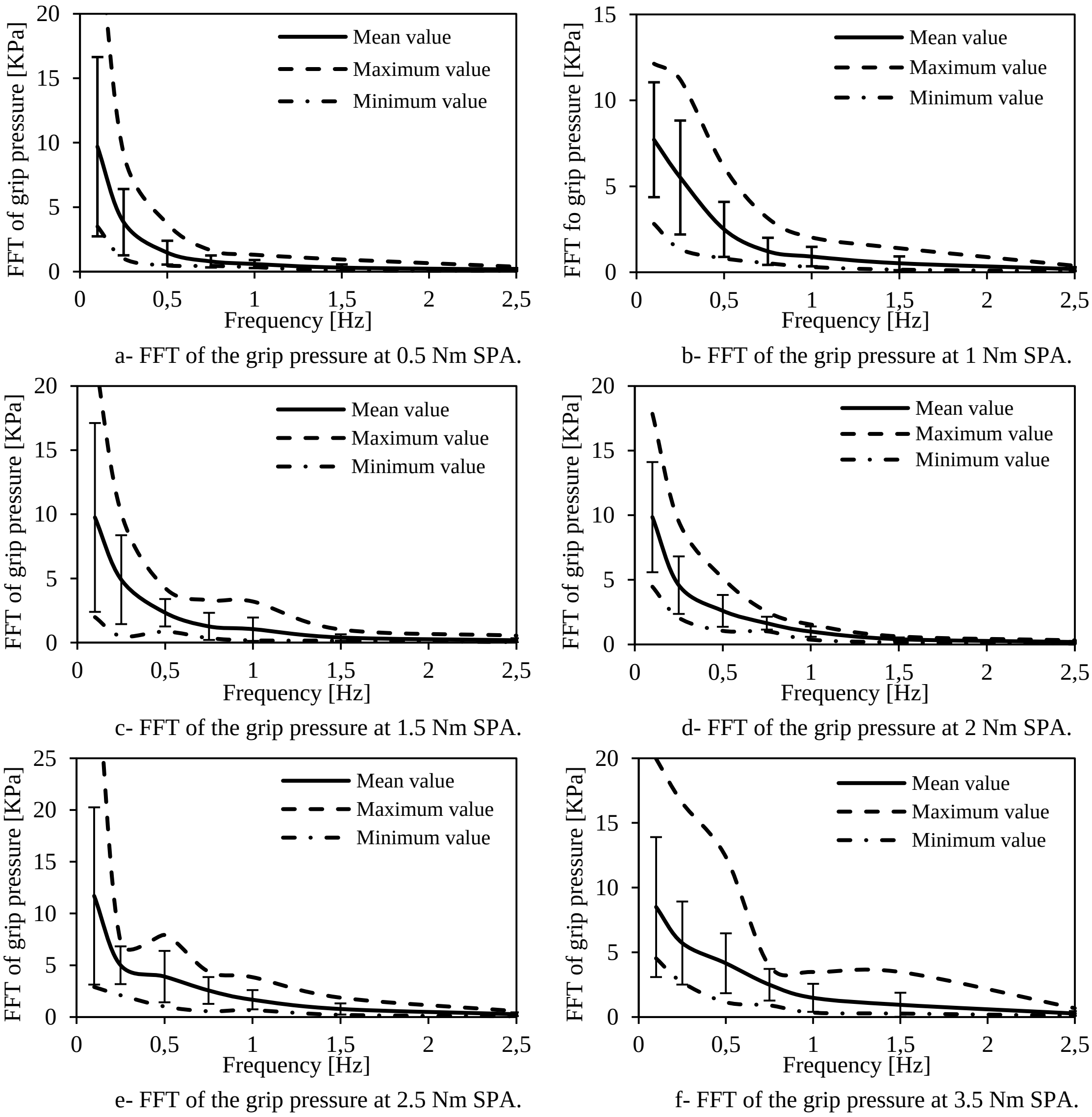
Results

5. *Results*

5.1. Estimation of mechanical arm admittance for real-time applications

5.1.1. Results: Estimated mechanical arm admittance without steering perturbations

In this section, the results of the experiment presented in the section 4.2.1. are introduced. The Figure 26 shows the average, min and max amplitude of the FFT of grip pressure.



a- FFT of the grip pressure at 0.5 Nm SPA.
b- FFT of the grip pressure at 1 Nm SPA.
c- FFT of the grip pressure at 1.5 Nm SPA.
d- FFT of the grip pressure at 2 Nm SPA.
e- FFT of the grip pressure at 2.5 Nm SPA.
f- FFT of the grip pressure at 3.5 Nm SPA.

Figure 26. Average of the Fast Fourier transform of the grip pressure applied by the drivers on the steering wheel during the estimation of mechanical arm admittance.

It can be observed that the amplitudes of the FFT of grip pressure become negligible quickly as the frequencies increase. It expresses that participants present high grip force at low frequency steering perturbations, and conversely. In the Figure 27, the amplitudes of mechanical arm admittance of every participant for the different steering perturbation amplitudes are presented. They were evaluated while the grip pressure of participants was recorded using glove on which grip pressure sensors were attached. The phase of mechanical arm admittance of this study is presented in Appendix.

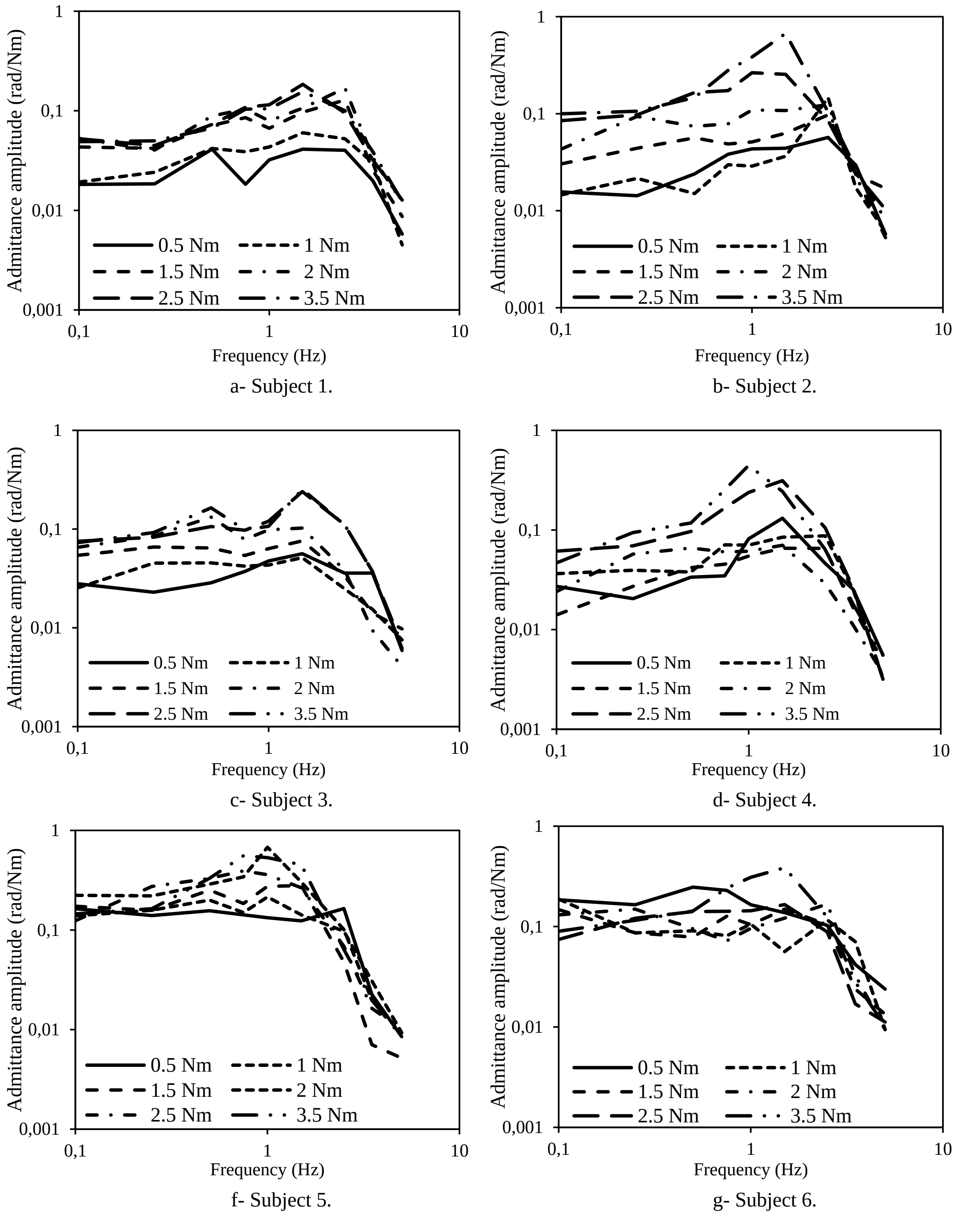
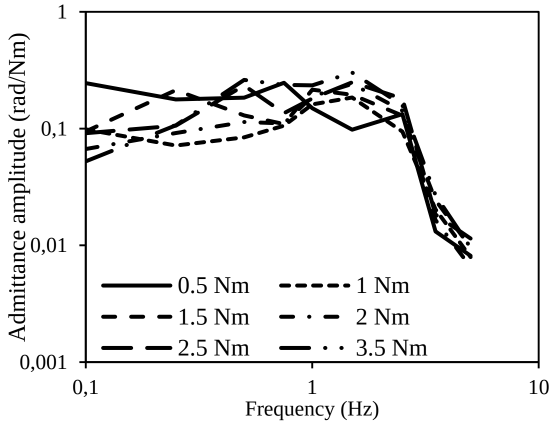
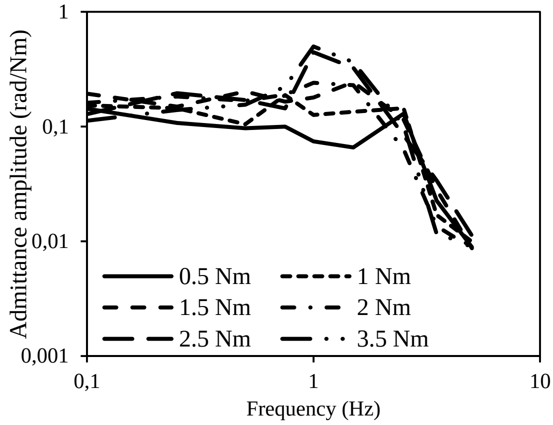


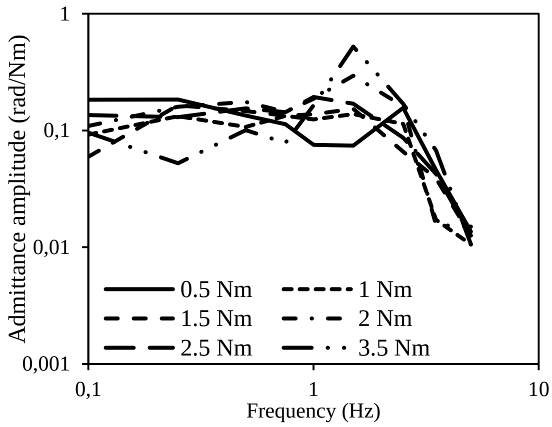
Figure 27.a. Estimation of the amplitude of mechanical arm admittance for the different amplitude of steering perturbation.



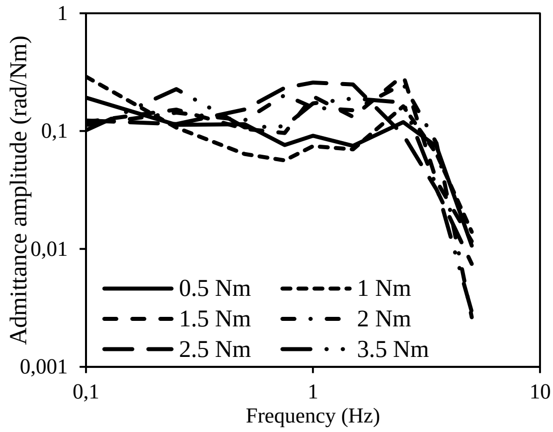
h- Subject 7.



i- Subject 8.



j- Subject 9.



k- Subject 10.

Figure 27.b. Estimation of the amplitude of mechanical arm admittance for the different amplitude of steering perturbation.

In the Figure 28, the squared coherence of mechanical arm admittance is presented and represent the reliability of the estimation of the neuromuscular condition of the driver. It is confirmed the squared coherence are superior than 0.5, which is used as a confirmation for the understanding of the amplitude of mechanical arm admittance.

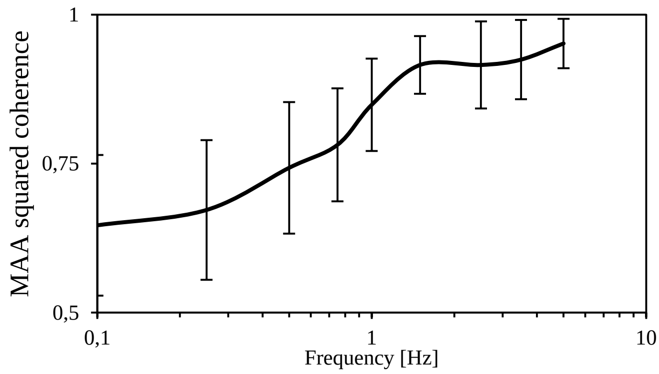


Figure 28. Coherence of mechanical arm admittance.

In the Figure 29, the relationship between the amplitude of mechanical arm admittance and the FFT of grip pressure is presented for each participant. As similar patterns were detected in the data set, it was decided to investigate tendencies of data by applying tendency curves to upper boundaries of plotted data, as described in the methodology section.

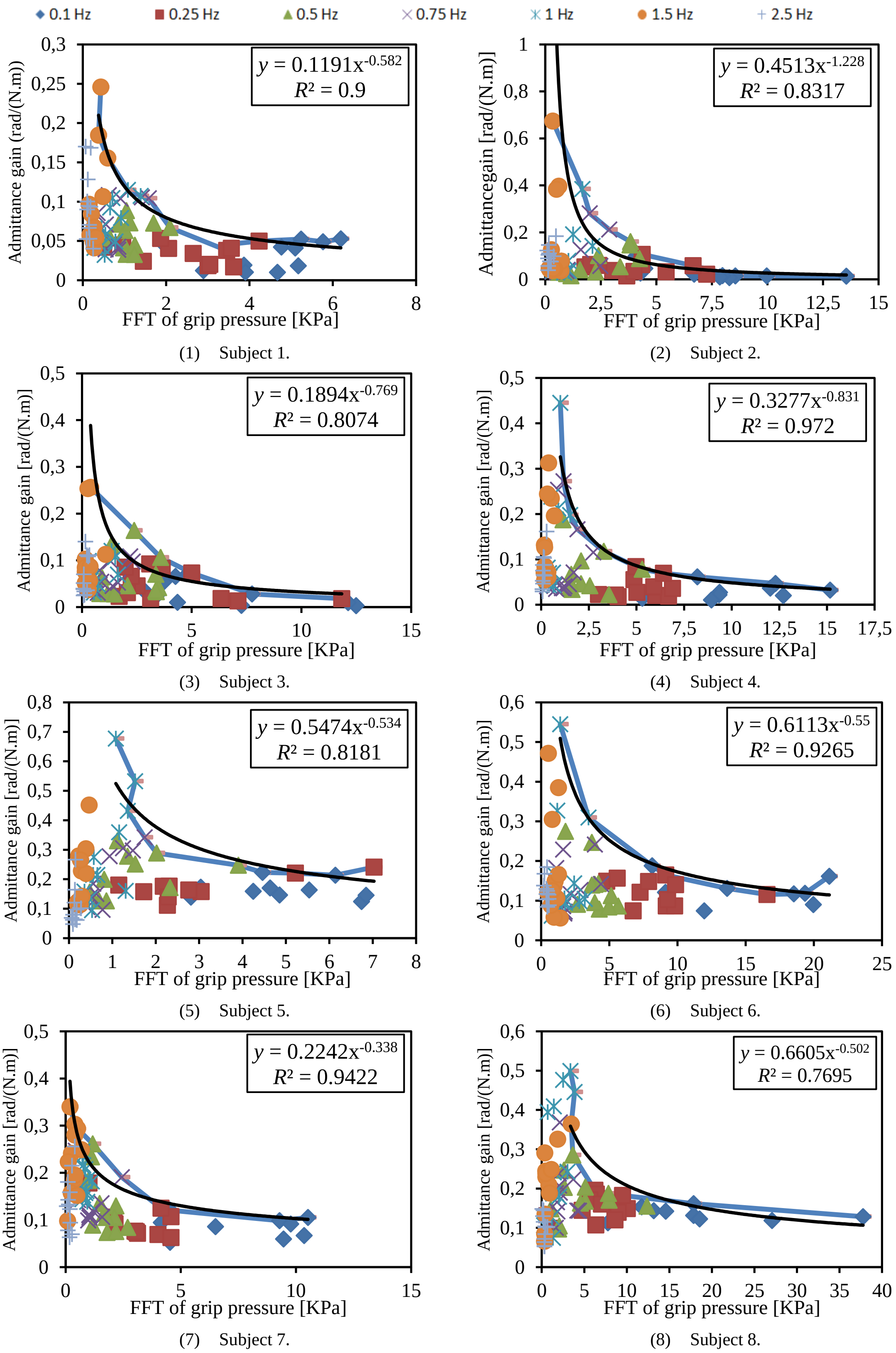
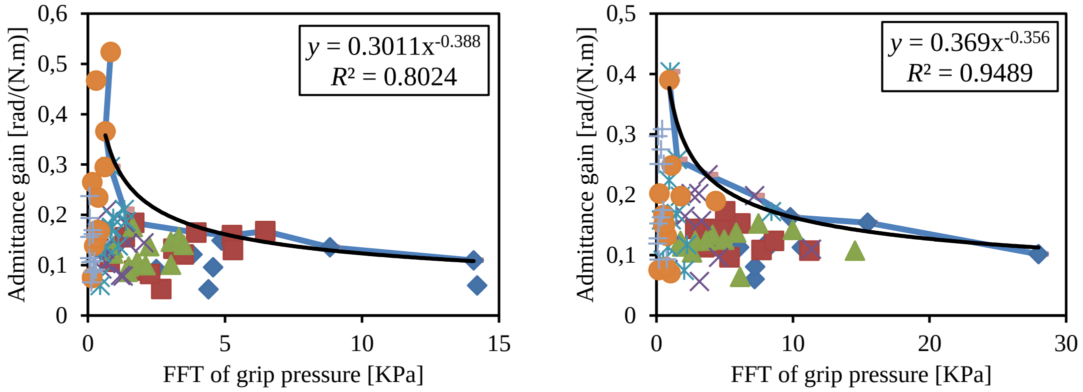


Figure 29.a. Relationship between mechanical arm admittance and grip pressure at corresponding stimulated frequencies.



(9) Subject 9. (10) Subject 10.

Figure 29.b. Relationship between mechanical arm admittance and grip pressure at corresponding stimulated frequencies.

It was found that coefficients of determination R^2, which can be observed in the legend of Figure 29, were at least better than 0.75, which indicated a high reliability of the estimation.

In order to observe the repartition of the data for each participant, it was decided to plot the area of data that are limiting the relationship between mechanical arm admittance and grip pressure on the same figure, which can be observed in in the Figure 30.

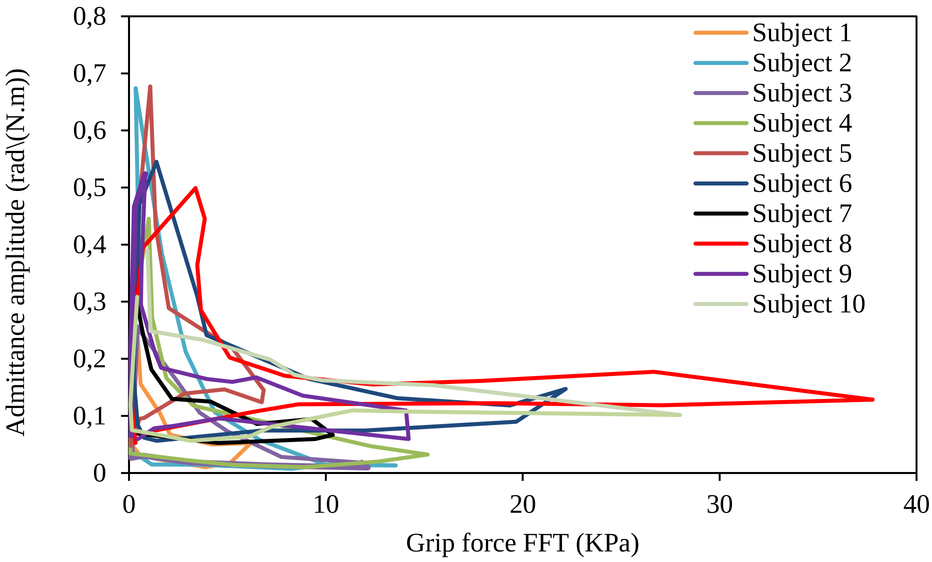


Figure 30. Individual areas of the relationship between mechanical arm admittance and grip pressure stimulated by the different participants.

It can be observed in the Figure 30 that the repartition of data is different for each participant but present a common pattern. In order to compare results on the same scale, delimiting curves from each participants were normalized. The normalization method employed gathers data on a 1-1 scale. This method was employed because of differences in the physical capacities of participants. Indeed, some participants produced higher grip pressure which had an impact on both the mechanical arm admittance gain and grip pressure. Figure 31 shows the results of the normalization method.

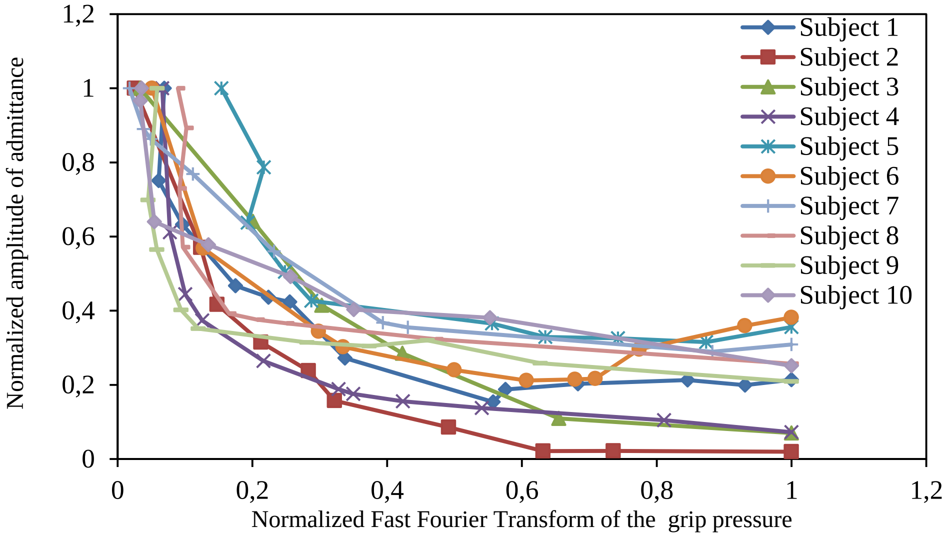


Figure 31. Normalized tendency curves of the relationship between mechanical arm admittance anf grip pressure for every participants.

A trend is observed in the Figure 31, which highlights that data are included in a characteristic strip. Although coefficients of determination R^2 of normalized data and normalized coefficients *b* remained identical, normalized coefficients *a* were affected by the normalization method. Table 3 presents the normalized coefficients *a* and *b*, which define tendency curves, and the normalized coefficients of determination R^2. It can be observed in Table 3 that the coefficients *a* and *b* of tendency curve varied considerably among the participants.

Table 3. Normalized coefficients a, b and R^2 for each participant (a and b refer to coefficients of equation 12).

	a	b	R^2
Subject 1	0.1677	−0.582	0.9
Subject 2	0.0272	−1.228	0.8317
Subject 3	0.1106	−0.769	0.8074
Subject 4	0.0768	−0.831	0.972
Subject 5	0.2852	−0.534	0.8181
Subject 6	0.2328	−0.55	0.9265
Subject 7	0.2976	−0.338	0.9422
Subject 8	0.2137	−0.502	0.7695
Subject 9	0.2064	−0.388	0.8024
Subject 10	0.2791	−0.356	0.9489

In the following paragraph, a discussion on the proposed method to estimate mechanical arm admittance without steering perturbation is presented.

In this experiment, participants experienced various perturbation signals that aim to stimulate distinct frequencies and amplitudes, while their grip pressure applied to the steering wheel was recorded. This was performed to investigate the relationship between the grip pressure applied to the steering wheel and the amplitude of mechanical arm admittance. It can be observed that the coherence of the estimated mechanical arm admittance is lower at lower frequencies. Katzourakis et al. explained this phenomenon with the dynamics of driving simulator actuators that cannot reproduce accurate steering motion below 0.5 Hz [49]. Grip pressure of participants, measured with sensors built into gloves, was recorded and transformed into frequency domain in order to associate the gain of mechanical arm admittance and grip pressure at the frequencies and amplitudes of steering perturbations. Fast Fourier transform of grip force was computed, as seen in the Figure 26, and results present similarities with the results of Schouten et al. [36]. It confirms that the acquisition of the grip pressure of participants was efficient during the experiment. Afterwards, the gain of mechanical arm admittance and the FFT of grip pressure were linked to establish the relationship between these variables. It can be observed in the Figure 29, which presents this association, that high grip pressures, combined with low mechanical arm admittance gains, were observed at low steering perturbation frequencies, and conversely. It highlights that drivers were more capable of countering the action of low frequencies steering perturbations. Indeed, it becomes more difficult to control the steering wheel when high frequencies excitations are applied on it, resulting in a less accurate control of the wheel and an increase in mechanical arm admittance gain and a decrease of grip pressure of participants. This also confirmed that the mechanical arm admittance and grip pressure performed jointly. Furthermore, it was established that higher mechanical arm admittance gains were observed when higher steering perturbation amplitude was applied on the steering wheel, as it was also reviewed by Abbink et al. [67]. This can be explained by the expectations of the study and have been reviewed by similar studies [68]. Indeed, participants were instructed to stiffly counter the actions of steering perturbations and steer to the maximum of their capability. The steering entropy then increased with the increase in steering perturbations and consequently the mechanical arm admittance gain was augmented. The association of the gain of mechanical arm admittance and the FFT of grip pressure present similar behaviours among participants. Indeed, it can be observed in the Figure 29 that high mechanical arm admittance gains were observed for the low FFT of grip pressure, and inversely. Furthermore, these results express that data are limited by an upper boundary, which is similar for every participant. Consequently, it was decided to define the relationship between mechanical arm admittance and grip pressure by the limiting feature of data for each participant, which is the upper boundary, and recurrent behaviours were investigated. Tendency curves, which their characteristics were to fit a power function as described in methodology section, were applied to upper boundaries of data for each participant. The coefficients of the power functions can be observed in the legend of the Figure 29. The coefficients of determination R^2, which indicate the degree of reliability of the estimation, were high for every participant. Whereas, the characteristic coefficients *b* of each equation did not indicate that the tendency curves fitted an inverse function as the power coefficients *b* were not equal to −1. Consequently, it can be said that the mechanical arm admittance is a power function of the arm stiffness, of which the characteristics depend on a person’s physical aspect. Since differences in scale were observed in the Figure 30, which are caused by individual difference in the strength of participants, upper boundaries of Figure 29 were normalized and compared on a 1-1 scale. The result of this comparison can be observed in the Figure 31 and the normalized characteristics coefficients of the power functions *a*, *b* and R^2 can be observed in Table 3. This method was employed in previous studies to find recurrent behaviours among population with individual differences [69][70]. The result of the normalization proved that a tendency could be observed as data are included in a strip but cannot be used as a reference for every driver. Indeed, from the human factor perspective, the results in the Figure 29 show a tendency indicating that the grip pressure and mechanical arm admittance were linked. Whereas, from an engineering control perspective, the characterization of the relationship had to be made individually according to results of Table 3, which shows a high degree of reliability but also a high variability in the characteristics coefficients a and b of the power functions. To sum up, drivers must be monitored individually and the investigated relationship for each driver must be known beforehand. In the following paragraph a conclusion is made on the content of this section.

This study concentrates on the relationship between grip pressure of drivers and mechanical arm admittance, which is a driving-based variable used to reliably define arm stiffness during driving. To achieve this target, participants experienced various steering perturbations while the grip pressure applied to the steering wheel was recorded. Mechanical arm admittance and grip pressure were linked in the frequency domain and the following conclusion could be made:

1. Mechanical arm admittance is a power function of the grip pressure for which its characteristic coefficients depend on the physical characteristics of the participants.

2. Normalization of data highlighted that a recurrent tendency was observed for every participant, but also indicated that the physical differences between participants led to individual differences. Moreover, participants highlighted higher mechanical arm admittance gains at higher frequencies of the human dominant motion control, which indicates a poor steering control at high steering frequencies.

5.1.2. Results: The amplitude scale of mechanical arm admittance

In this section, the results of the experiment presented in the section 4.2.2. are introduced. In the Figure 32, the different amplitudes of mechanical arm admittance for the different amplitudes of steering perturbations are presented. The phase of mechanical arm admittance of this study is presented in Appendix.

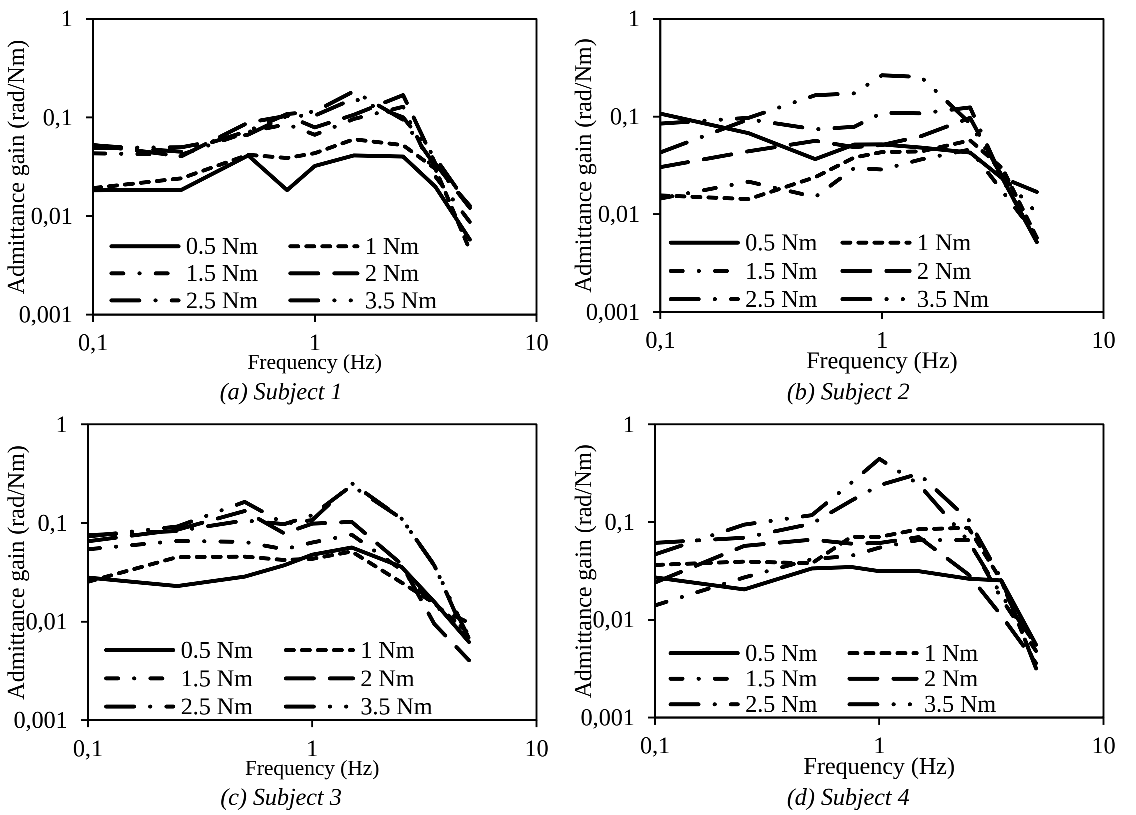


Figure 32. Estimated mechanical arm admittance at different amplitude of steering perturbations.

In the Figure 33, the squared coherence of mechanical arm admittance is presented and represent the reliability of the estimation of the neuromuscular condition of the driver. It is confirmed the squared coherence are superior than 0.5, which is used as a confirmation for the understanding of the amplitude of mechanical arm admittance.

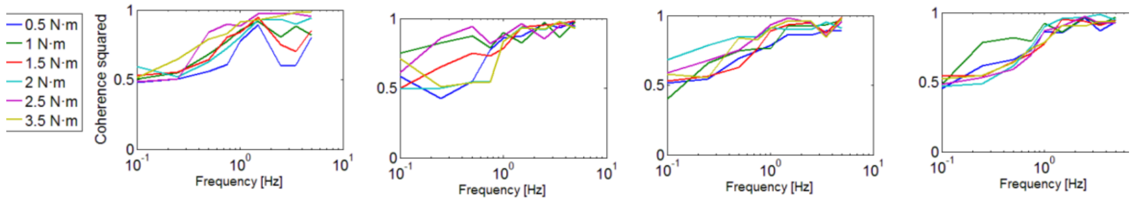


Figure 33. Coherence of mechanical arm admittance.

It can be observed in the Figure 32 that the amplitudes of mechanical arm admittance tend to increase with the increase of the amplitude of the steering perturbations. Moreover, the ranges of amplitude of mechanical arm admittance of each participant were displayed on the same graph as.

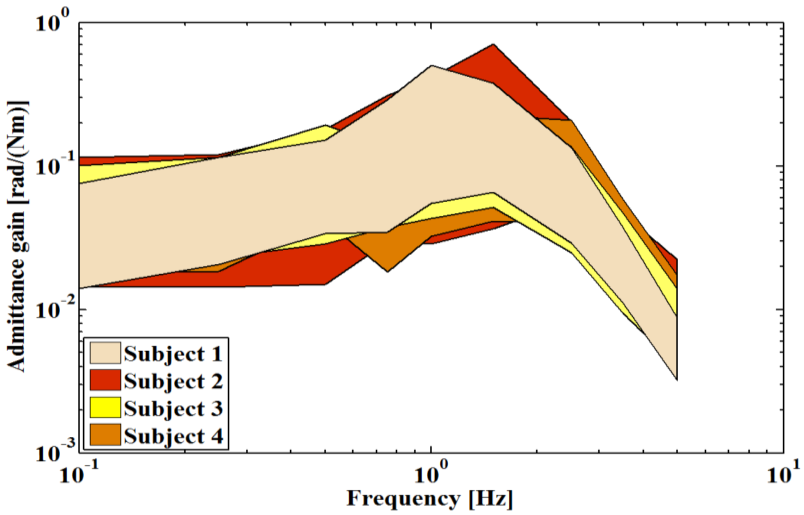
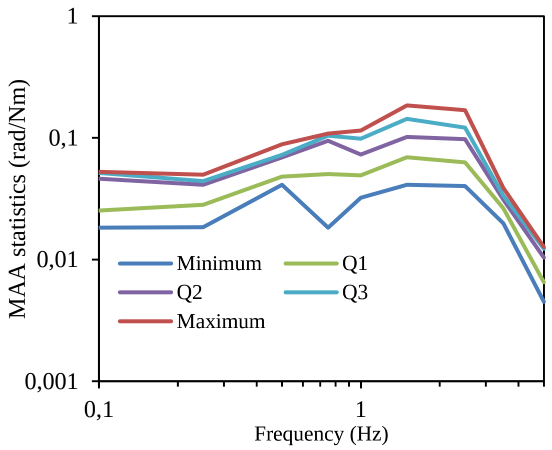
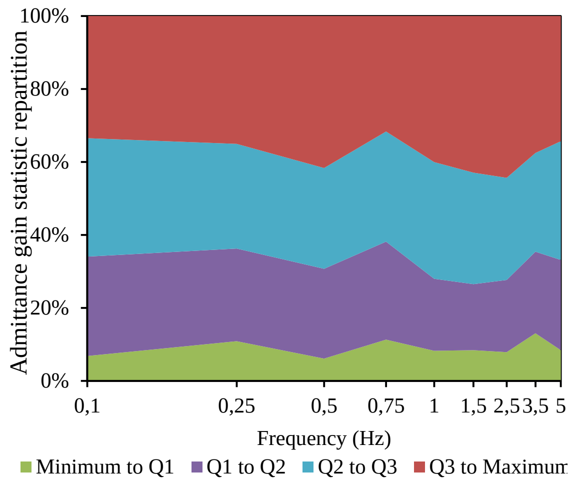


Figure 34. Range of amplitudes of mechanical arm admittance of participants.

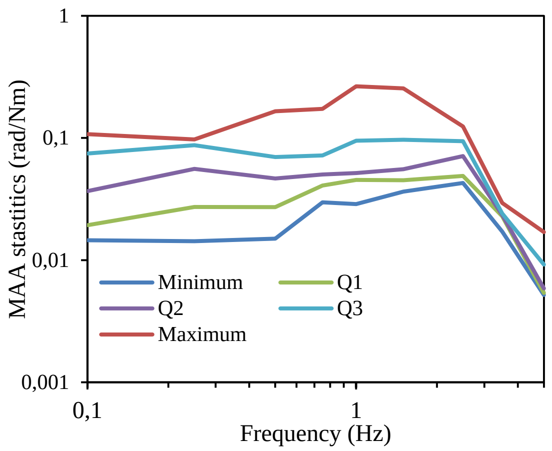
In this experiment, the number of participants is low because of the nature of the investigation. Indeed, this study aims to investigate the difference in amplitude of mechanical arm admittance in order to observe the difference in scale of mechanical arm admittance and repartition of amplitude of mechanical arm admittance between participants. In case participants present similar scales of mechanical arm admittance, it would express that a universal scale of mechanical arm admittance can used for every driver to investigate the variations of mechanical arm admittance in real-time. However, this assumption is denied by the review of Figure 34 since few participants already present a difference in scale of mechanical arm admittance that expresses the difference in neuromuscular condition of the participants of the experiment. In the Figure 34, participants present higher arm stiffness at lower amplitude of mechanical arm admittance because the can resist better to steering perturbations that do not induce large deviations on the steering wheel. Thus, it was decided to investigate the statistic repartition of the amplitude of mechanical arm admittance in order to be able to emit a statement on the scale repartition of mechanical arm admittance, aiming to perform a real-time monitoring. The minimum value, Q1, Q2, Q3 and the maximum value of the amplitude of MAA were computed and presented in the Figure 35.

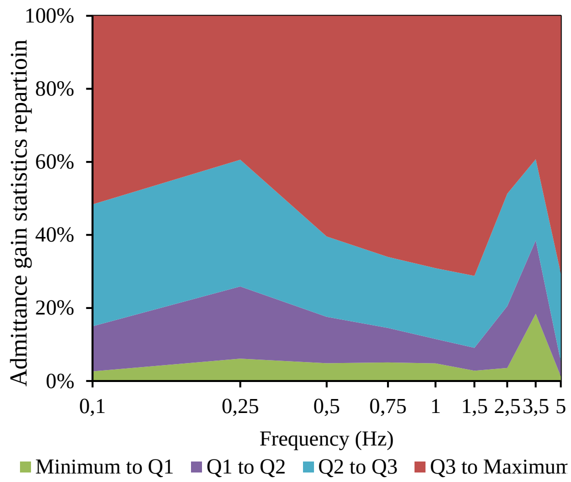




a1. Minimum, 1st, 2nd and 3rd quartile and maximum values of gain of mechanical arm admittance of subject 1.

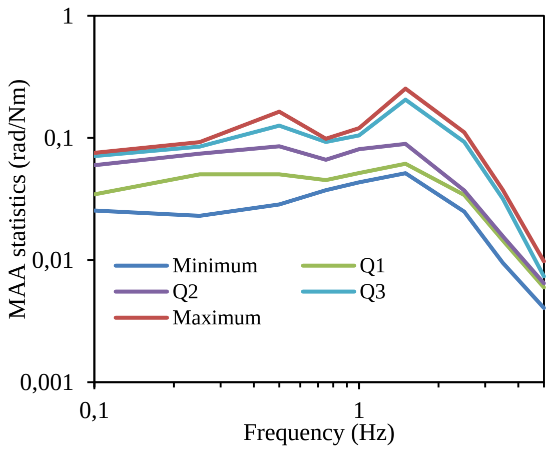
a2. Statistic repartition of quartiles of admittance gain as a percentage of minimum and maximum gain of subject 1.

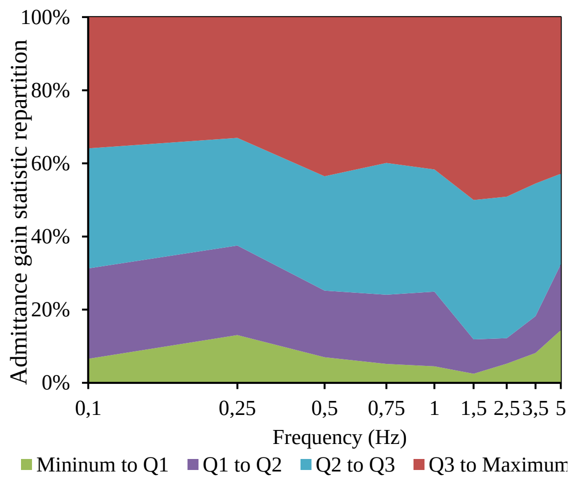




b1. Minimum, 1st, 2nd and 3rd quartile and maximum values of gain of mechanical arm admittance of subject 3.

b2. Statistic repartition of quartiles of admittance gain as a percentage of minimum and maximum gain of subject 2.

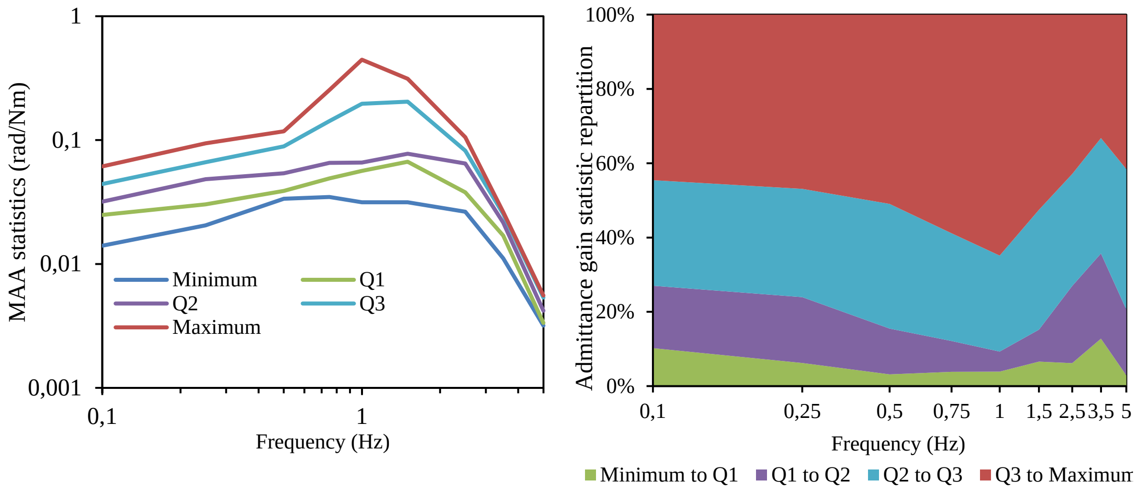




c1. Minimum, 1st, 2nd and 3rd quartile and maximum values of gain of mechanical arm admittance of subject 2.

c2. Statistic repartition of quartiles of admittance gain as a percentage of minimum and maximum gain of subject 3.

Figure 35.a. Statistical repartition of the amplitude of MAA between the minimum and maimum value.



d1. Minimum, 1st, 2nd and 3rd quartile and maximum value of gain of mechanical arm admittance of subject 4.

d2. Statistic repartition of quartiles of admittance gain as a percentage of minimum and maximum gain of subject 5.

Figure 35.b. Statistical repartition of the amplitude of MAA between the minimum and maimum value.

On the left side, the minimum value, the first quartile, the second quartile, the third quartile and the maximum value of the amplitude of mechanical arm admittance are presented on a non-modified scale. On the right side, the repartition of the quartiles compared to the minimum amplitude of mechanical arm admittance, 0%, and the maximum value of mechanical arm admittance, 100%, is presented. This was computed to know the range of mechanical arm admittance influence of participants.

The average repartition in percentage of the amplitude of mechanical arm admittance between the maximum value (100%) and the minimum value (0%) is presented in the Figure 36.

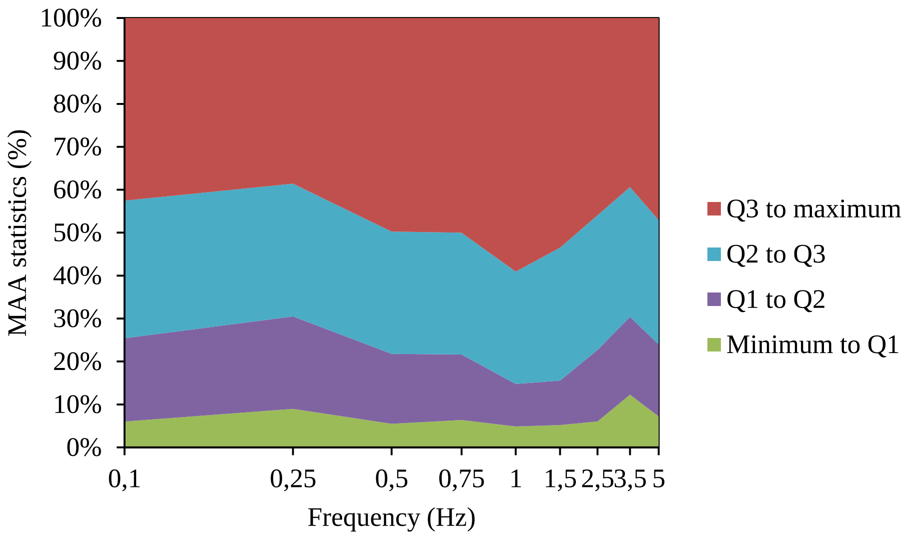


Figure 36. Average statistical repartition in percentage of mechanical arm admittance between the maximum and minimum observed amplitudes.

It can be observed that the decrease in amplitude of mechanical arm admittance is not linear. Indeed, it can be observed in the Figure 36 that the quartile repartition of amplitudes of mechanical arm admittance between the maximum amplitude of mechanical arm admittance and the minimum amplitude of mechanical arm admittance is non-linear, as the quartile repartition of amplitude of mechanical arm admittance between 0% and 100% is irregular. In the following paragraph, a discussion on the proposed method to estimate scale of amplitude of mechanical arm admittance to permit its estimation for real-time application is presented.

Upper and lower extremities of amplitude of mechanical arm admittance represent limits capacities of drivers to resist to steering perturbations. Since the participants performed a PT, it was observed that the amplitude of mechanical arm admittance increases with the increase of mechanical arm admittance. The Figure 32 presents this scale for each subject and the Figure 34 present the superposition of these scale for all participants. It is observed in the Figure 34 that this scale is different for each participant, as they have different upper limbs characteristics. Consequently, the mechanical arm admittance scale of each driver is unique. The knowledge of this scale can be acquired beforehand, when the vehicle is stopped for example, and used as a baseline to determine the NMS of the driver in real-time conditions. Indeed, this operation appears as a calibration of the driver capacities to react to steering perturbations and must be considered to ensure the safety of the driver in difficult driving situation. Moreover, assistance system can provide assistance torque on the steering wheel based on the comparison of real time data with the scale of reference of the driver. For example, if drivers show high mechanical arm admittance (which expresses relax driving under low perturbation amplitude or tensed driving under high perturbation amplitude), steering assistance system increase the influence of corrective torque to adjust the trajectory of the vehicle.

Moreover, it is observed in the Figure 36 that the average repartition of the amplitude of mechanical arm admittance between its maximum and minimum values is not linear. Indeed, the first quartile presented in the Figure 36 is concentrated regarding the final repartition, which indicates that low mechanical arm admittance amplitudes are very concentrated (green area), at the opposite of high mechanical arm admittance amplitudes that are scattered. It means that participants show consistent behaviour at low mechanical arm admittance amplitude, i.e. they show consistent behaviour when resisting to low steering perturbation amplitude. At the opposite, participants show dispersed behaviour at high amplitude of mechanical arm admittance, i.e. they show disperse behaviour when resisting to high steering perturbation amplitudes. This fact must also be taken in consideration by the assistance system since the transition in amplitude must be predicted to apply smooth steering feedbacks. In the following paragraph a conclusion is made on the content of this section.

In this study, a method for investigating the range of amplitude of mechanical arm admittance is proposed. This knowledge is used as a reference for real-time monitoring of mechanical arm admittance. Based on the proposed method and the statistical repartition in amplitude of mechanical arm admittance, the following conclusions were made

1. Mechanical arm admittance can be estimated beforehand for real-time application.
2. The repartition of mechanical arm admittance between its maximum and minimum value is not linear, indicating that the upper limb behaviour reaction to steering perturbation is not linear.

5.2. Detection of impaired condition using mechanical arm admittance

5.2.1 Results: Drowsiness detection using mechanical arm admittance

In this section, the results of the experiment presented in the section 4.3.1 are introduced.

Drowsiness of driver was assessed by observing the evolution of self-evaluation drowsiness test scores and the values of blink duration and eyelid amplitude to velocity ratio. The Figures 37 and 38 present the average blink durations of drowsy participants and the mean amplitude-velocity ratio of drowsy participants respectively over the entire drive. The quality of the eyelid motion acquisition by SmartEye during the drowsy stage of the experiment is presented in the following table.

Table 4. Quality Q of the eyelid motion acquisition from SmartEye data

Subject	1	2	3	4	5	6	7	8	9	10
Q	0.98694	0.97340	0.87371	0.99337	0.99913	0.99640	0.96547	0.99657	0.98574	0.97845
STD	0.07354	0.12469	0.22312	0.03468	0.01245	0.02526	0.12658	0.02031	0.09484	0.15312

The quality of the eye-tracking was very high thanks to the camera setup accuracy as well as the strong focus on the eyelid motion calibration to ensure the quality of the recording. It is observed in Figures 37 and 38 that average values of blink duration and eyelid amplitude to velocity ratios are higher than drowsiness thresholds.

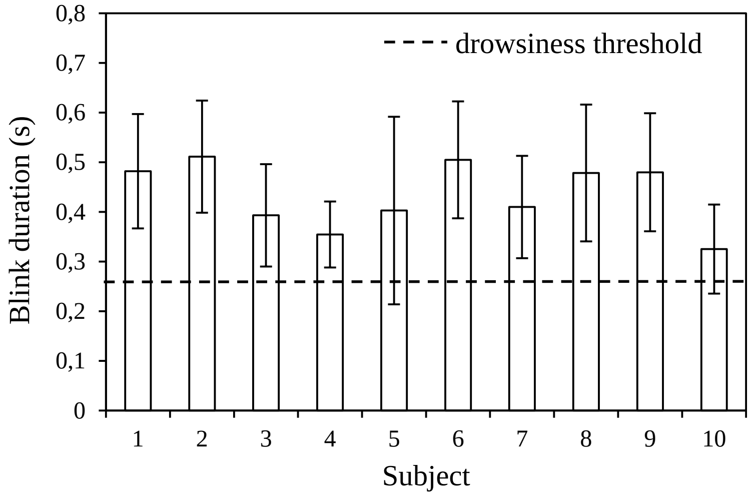


Figure 37. Mean blink duration during the expected drowsy state.

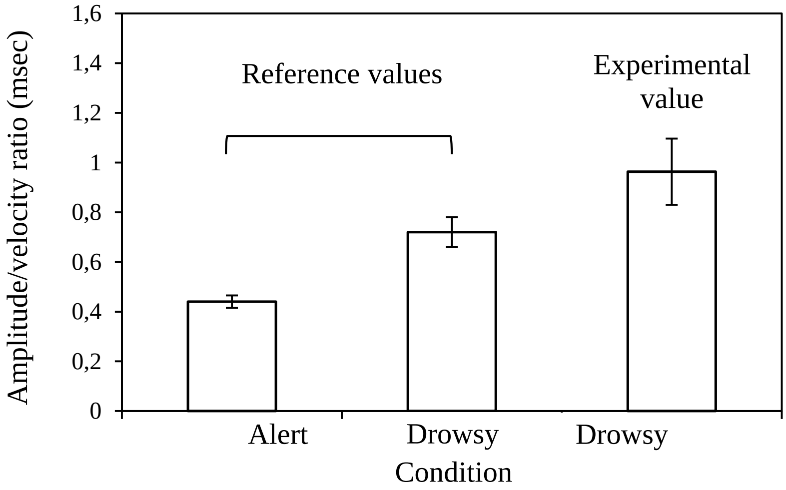


Figure 38. Mean amplitude to velocity ratio for drowsy and alert participants.

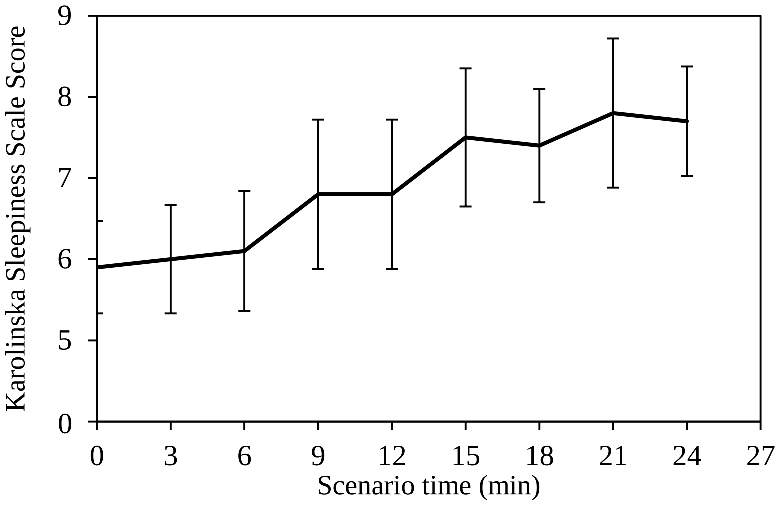


Figure 39. Evolution of mean score of Karolinska Sleepiness Scale. (score 5 = neither sleepy, nor alert; score 6 = some sign of sleepiness; score 7 = sleepy, no effort to keep awake; score 8 = sleepy, some effort to keep awake; score 9 = very sleepy, fighting sleep).

Moreover, the evolution of scores of Karolinska sleepiness scale test, shown in the Figure 39, presents an increase as the experiment time increases. It denotes that drowsiness of drivers increased due to the monotony of the scenario. Furthermore, the Time of Day Sleepiness Scale score rated by participants before the experiment presents an average value of 6.9 ± 2.88 out of 24 in the afternoon, which does not indicate a high probability of falling asleep for the alert stage of the experiment. As an indicator of drowsiness background, it expresses that drivers were alert for the second stage of the experiment.

In following, the estimation of the amplitudes of mechanical arm admittance for every participant of this experiment is presented. The phase of mechanical arm admittance of this study is presented in Appendix.

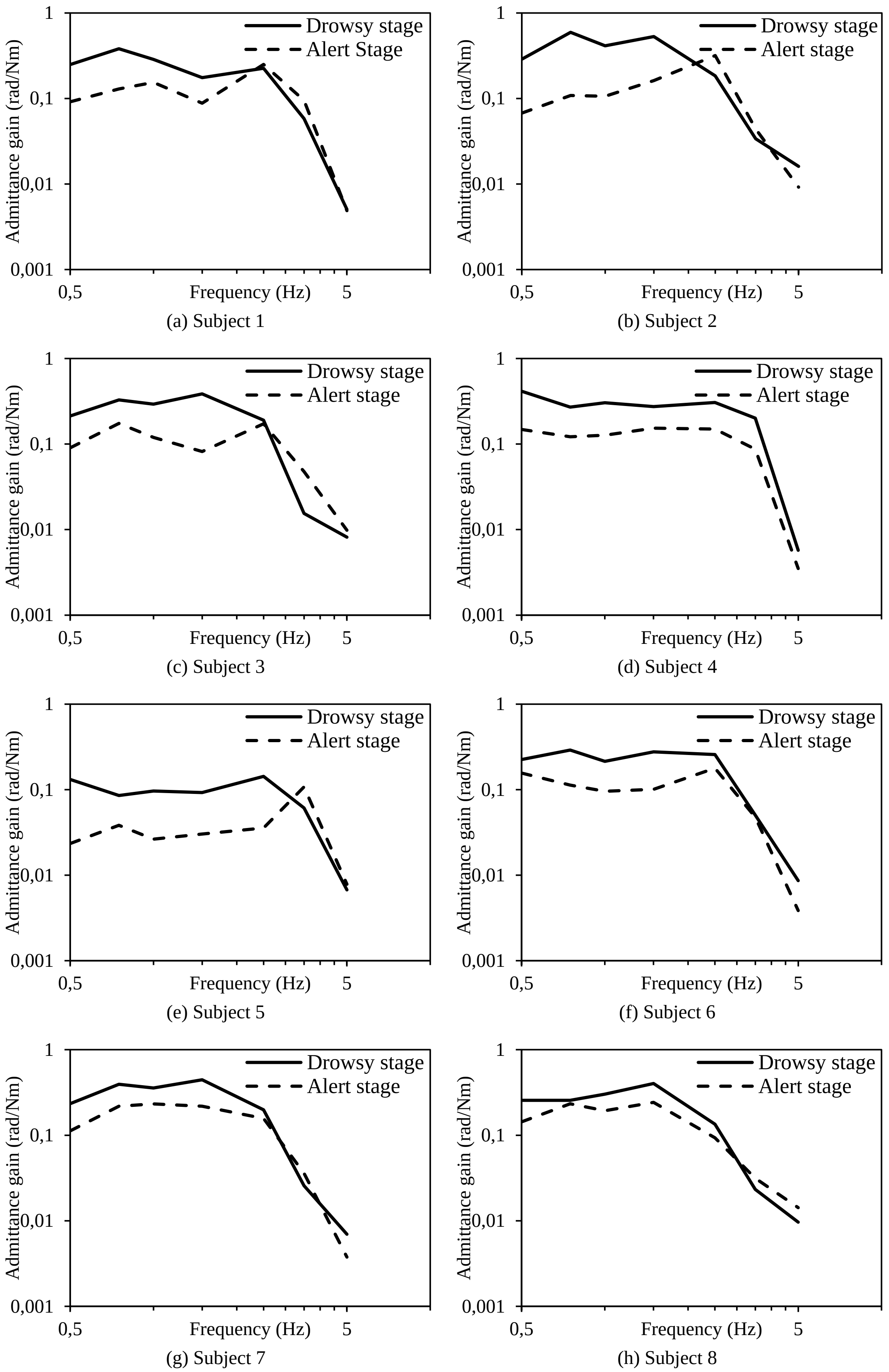
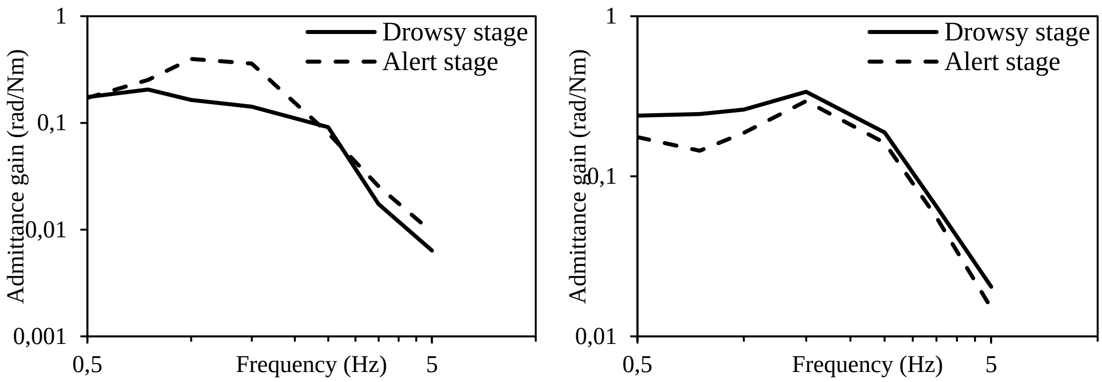


Figure 40.a. Estimation of the amplitude of MAA of participants at drowsy and alert stages.



(i) Subject 9 (j) Subject 10

Figure 40.b. Estimation of the amplitude of MAA of participants at drowsy and alert stages.

It can be observed in the Figure 40 that the amplitude of mechanical arm admittance of participants is usually higher during the drowsy stage of the experiment, which expresses a relaxed behaviour of the upper limb of the participants during this stage. In the Figure 41, the squared coherence of mechanical arm admittance is presented and represent the reliability of the estimation of the neuromuscular condition of the driver. It is confirmed the squared coherence are superior than 0.5, which is used as a confirmation for the understanding of the amplitude of mechanical arm admittance.

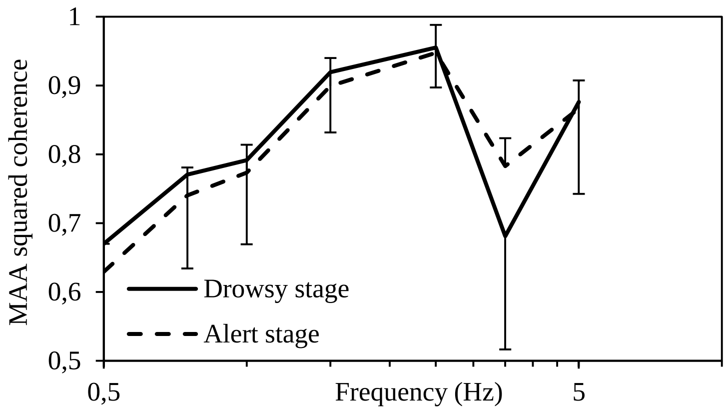


Figure 41. Coherence of mechanical arm admitance.

The average amplitudes of mechanical arm admittance for drowsy and alert stages are displayed in the Figure 42.

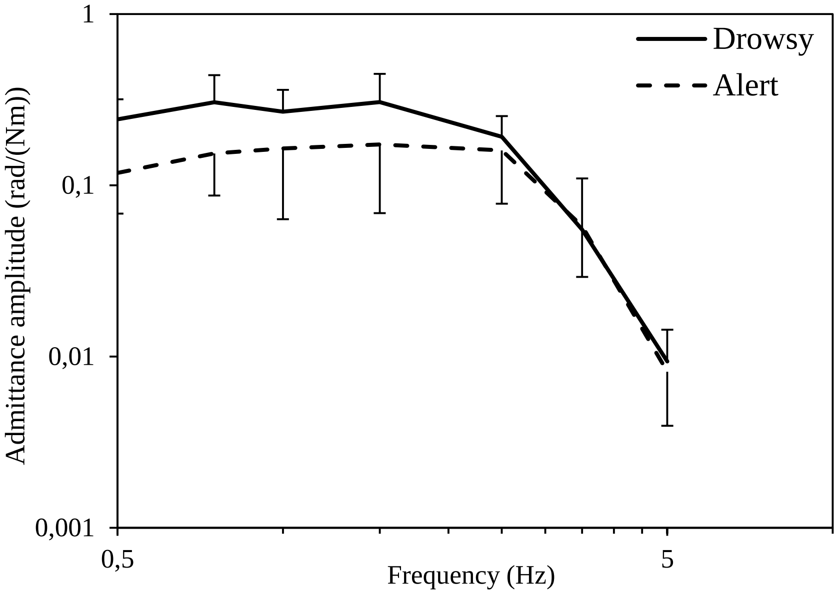


Figure 42. Average of the amplitude of mechanical arm admittance at drowsy and alert stages.

To determine whether drowsiness has a statistical impact on mechanical arm admittance gain, a two-way ANOVA with repeated measures was performed for the analysis of variance. Two independent variables, which are the condition of the driver (drowsy and alert) and the frequencies before the cut-off frequency (0.5, 0.75, 1, 1.5 and 2.5 Hz), were used for the statistical analysis. Beforehand, assumptions were verified as there were no outliers, as assessed by examination of studentized residuals for values greater then +/- 3, mechanical arm admittance amplitude was normally distributed, as assessed by Shapiro-Wilk's test of normality on the studentized residuals ($p > 0.05$). Mauchly's test of sphericity did not show any violation of sphericity.

It was found that a significant two-way interaction exists between the conditions of the drivers and the frequencies before the cut-off frequency: $p = 0.047 < 0.05$, F (4, 36) = 2.674. Post hoc comparisons using F-Test with Bonferroni correction that concerns mechanical arm admittance gain differences along frequency is presented in table 5. It can be observed in the Table 5 that the gains of mechanical arm admittance are significantly different between drowsy and alert states, for 0.5, 0.75 and 1.5 Hz. The gain of mechanical arm admittance presents a near-significant trend, $p = 0.072$, at 1 Hz.

Table 5. Report of single main effect between drowsy and alert states.

Frequency	*p*-value	*F*-value	Mean difference
0.5 Hz	0.001	$F(1, 9) = 26.515$	0.125
0.75 Hz	0.010	$F(1, 9) = 10.732$	0.152
1 Hz	0.072	$F(1, 9) = 3.821$	0.094
1.5 Hz	0.029	$F(1, 9) = 6.785$	0.133
2.5 Hz	0.225	$F(1, 9) = 1.694$	0.032

The table 5 expresses that the amplitude of mechanical arm admittance between the drowsy stage and the alert stage are significantly different. In the following paragraph, a discussion on the impact of drowsiness on mechanical arm admittance is presented.

It can be observed in the Figures 37 and 38 that the average values of blink duration and the amplitude-velocity ratio of eyelid reopening present values superior to the threshold observed in literature for defining drowsiness [10][71]. Moreover, self-evaluation of drowsiness by the Karolinska sleepiness scale questionnaire, which has been shown to be efficient in previous studies to assess the level of drowsiness, also show an increase of drowsiness score as the scenario continues as it can be noticed in the Figure 39 [72]. Indeed, participants rated their drowsiness as level 6 (some sign of sleepiness) at the start of the experiment, on average, and ended the experiment with an average value between level 7 (sleepy, but no effort to keep awake) and level 8 (sleepy, some effort to keep awake). This result confirms that an increase in driving task duration induces drowsiness which is similar to the report of Thiffault *et al.* [58]. Combining different assessments of drowsiness (questionnaire, eye-tracking data) has been found to be an efficient indicator of deprived sleep [73]. Consequently, minor modifications of the nutrition and the sleep cycle, and the increase in duration of driving task were effective to induce drowsiness during the first stage of the experiment. Furthermore, average score of the Time of Day Sleepiness Scale did not indicate a predisposition for sleepiness in the afternoon, which indicates that mechanical arm admittance during the second stage of the experiment was estimated for alert participants. The critical point in this study was to measure mechanical arm admittance of drowsy participants without interference or prior knowledge of the aim of the scenario. Since it was decided to perform the drowsy stage prior to the alert stage, the results may be affected by an order effect. Indeed, while performing the second stage of the experiment, the driver may remember the steering sensation caused by the steering disturbances during the evaluation of mechanical arm admittance and try to reduce their effects on their steering behaviour. This practice effect could affect the difference in mechanical arm admittance gain and change the results of the statistical analysis. Whereas, drowsiness is fluctuating state were the awareness of the driver is reduced and the experience gained from the drowsy driving is often negligible because of the incapacity of the drivers to provide accurate steering feedbacks, which also affect their perception during driving. Thus, it was decided to perform the drowsy stage at first in order to prevent driving reaction coming the experience of the drowsy stage of the experiment. Moreover, the experience gained from the drowsy stage is not problematic since driver are supposed to react as the maximum of their capacities during the alert stage of the experiment. As a result, the measurement of mechanical arm admittance during both stages of the experiment could be performed in conditions with negligible interferences.

It can be observed the Figure 42 that the amplitudes of mechanical arm admittance in both the drowsy and alert states are different until a certain frequency, which is confirmed by the statistical analysis. Therefore, drowsy drivers exhibit a relaxed driving in a specific frequency range from 0.5 to 2.5 Hz.

Low-frequency differences in mechanical arm admittance gain can be explained by the physical capacity and intrinsic characteristics of drowsy drivers. For low-frequency disturbances, alert drivers can minimize steering perturbations because they correspond to low-difficulty steering tasks. However, drowsiness induces impaired and drowsy drivers are less physically active [74]. Therefore, they do not express a tensed driving even at low frequencies, when they are supposed to be able to react in their alert condition. Furthermore, the reflex activity of the arm described in the literature expresses an increased power, which is limited to a bandwidth below 3 Hz, when performing the position task [67].

According to our results, drowsiness impacts negatively neuromuscular condition of drivers since it increases the gain of mechanical arm admittance in a certain frequency range of 0.5–2.5

Hz and leads to a relaxed driving. Outside of this spectrum, drowsy and alert drivers react similarly to steering perturbations due to the physical characteristics of participants that are limited to the previously cited frequency range. In the following paragraph a conclusion is made on the content of this section.

In this study, the effects of drowsiness on mechanical arm admittance was investigated in the frequency domain where human power is dominant for steering operation. Participants performed a PT to estimate mechanical arm admittance for drowsy and alert states. Mechanical arm admittance was estimated and its variations in gain were reviewed. There is a difference in the gain of mechanical arm admittance in the frequency range of 0.5–2.5 Hz. In this spectrum, the mechanical arm admittance of drowsy drivers is higher in gain, which shows their reduced attention on the driving task as well as more relaxed driving. This result shows impaired driving induced by drowsiness. Outside this bandwidth, participants react similarly to steering perturbations because of the frequency limitations of arm responses.

5.2.2 Results: The detection of cognitive distraction using mechanical arm admittance

In this section, the results of the experiment presented in the section 4.3.2. are introduced.

The results presented in this section are different from the publication, as additional advices were given to refine the analysis and increase the reliability of the results. The phase of mechanical arm admittance of this study is presented in Appendix.

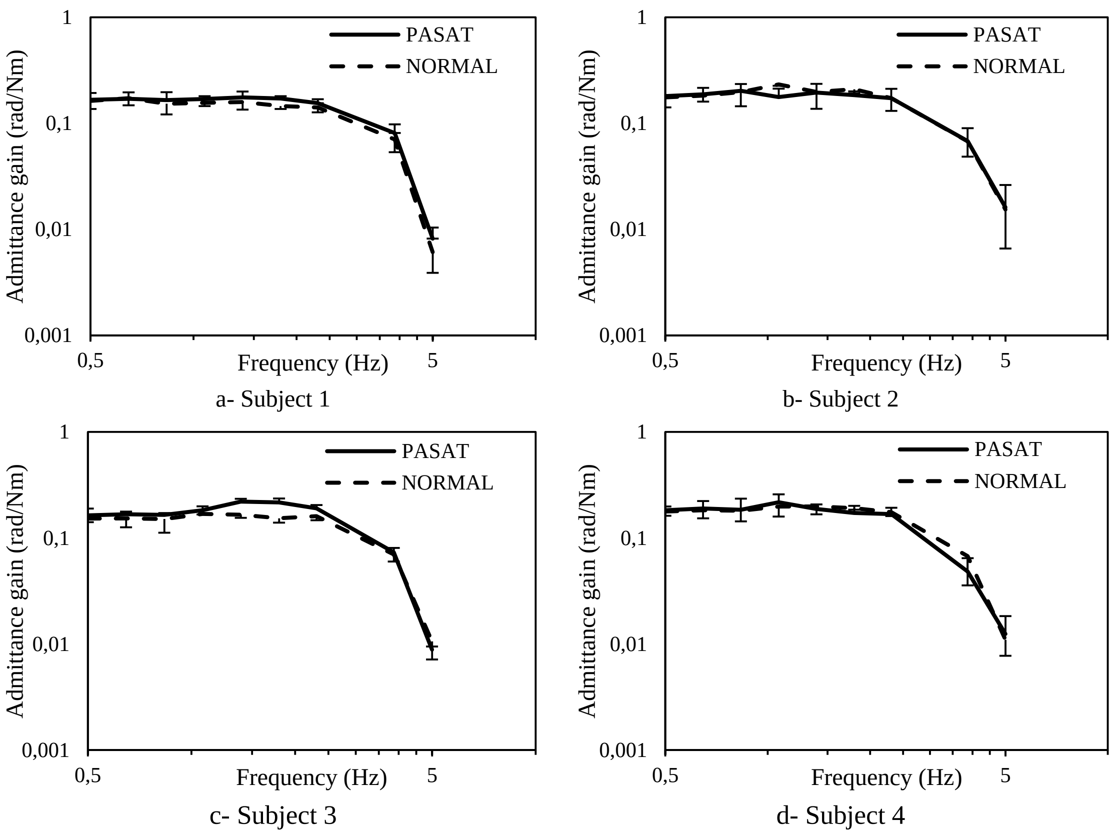


Figure 43.a. Amplitude of mechanical arm admittance for NORMAL and PASAT stages for each participant.

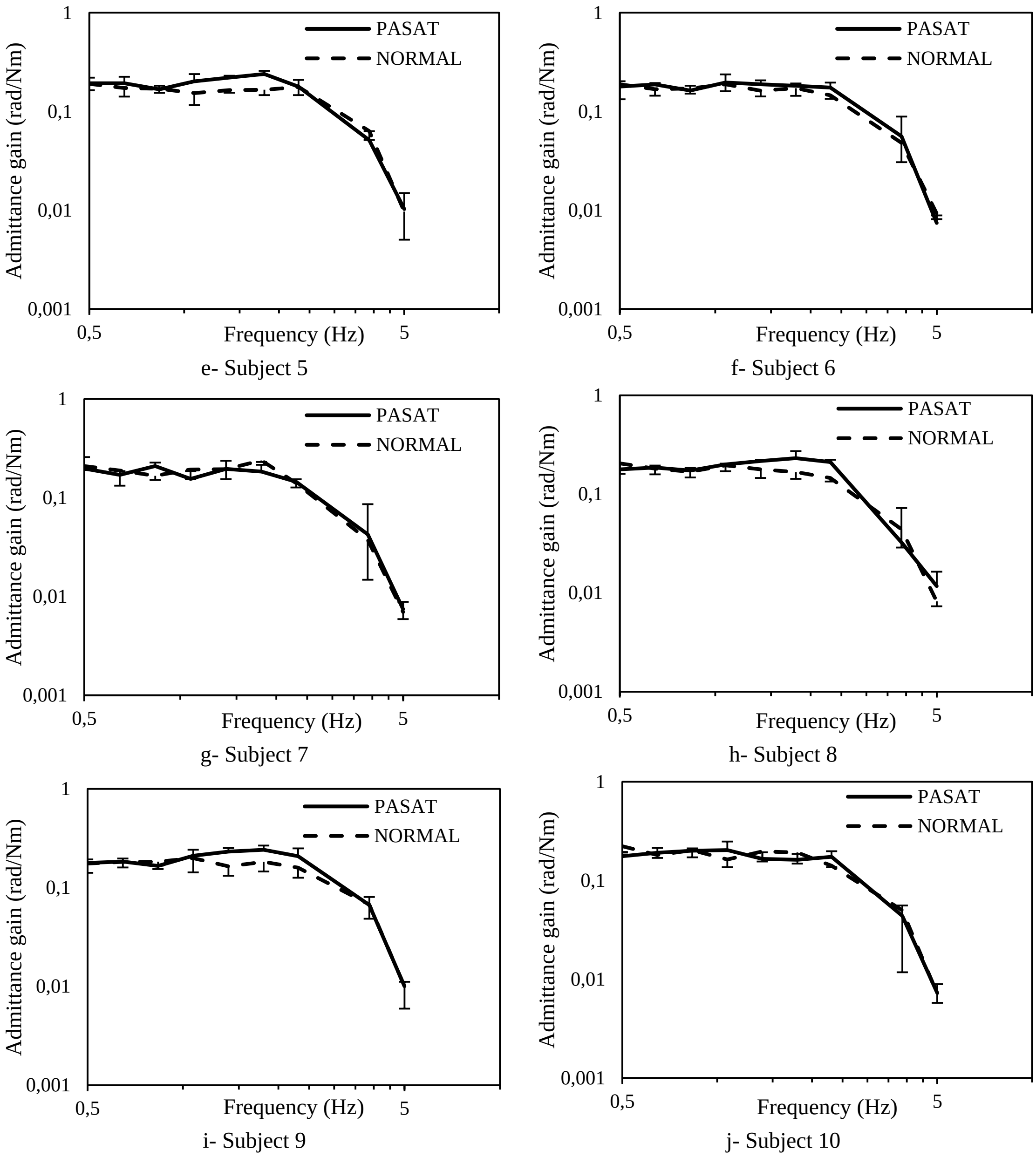


Figure 43.b. Amplitude of mechanical arm admittance for NORMAL and PASAT stages for each participant.

It can be observed in the Figure 43 that the amplitude of mechanical arm admittance presents two patterns between normal stage and PASAT stage. Indeed, it is possible to observe no difference for subjects Nos. 1, 2, 4, 6, 7 and 10 between the NORMAL stage and PASAT stage. This review denotes that the cognitive distraction method was not effective to induce mental distraction for these participants as they don’t present difference in their neuromuscular conditions.

In the Figure 44, the squared coherence of mechanical arm admittance is presented and represent the reliability of the estimation of the neuromuscular condition of the driver. It is confirmed the squared coherence are superior than 0.5, which is used as a confirmation for the understanding of the amplitude of mechanical arm admittance.

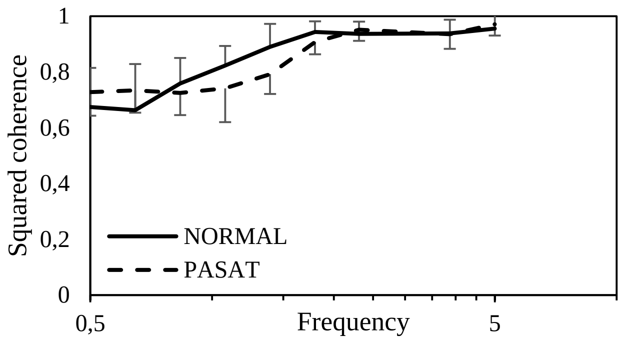
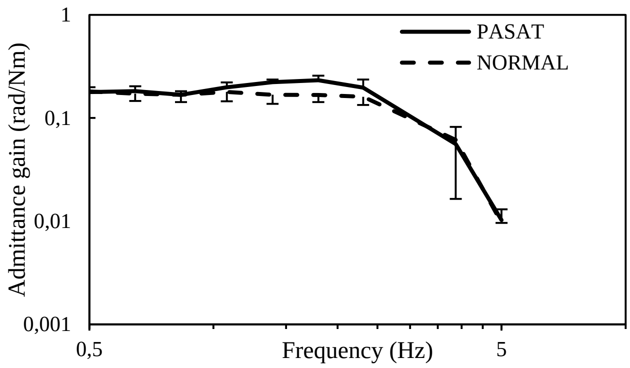
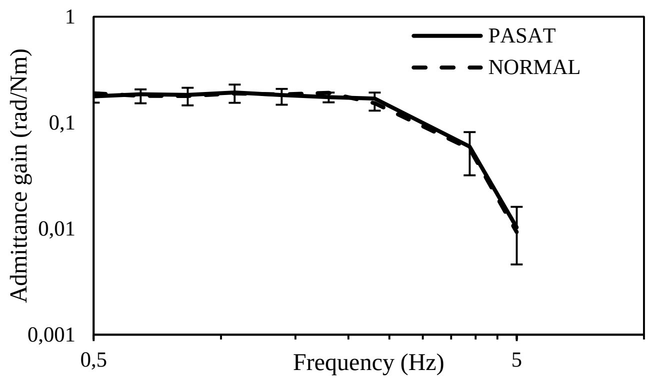


Figure 44. Coherence of mechanical arm admittance.

The distraction method used was easy enough for them to handle. However, difference in mechanical arm admittance can be observed for subjects Nos. 3, 5, 8 and 9. Indeed, for these participants, mechanical arm admittance is increased by the PASAT condition on a certain frequency range. In order to clearly see these differences, the average of amplitude of mechanical arm admittance for the two previously cited categories of participants was computed and displayed in the Figure 45. It can be observed in the subfigure 45.a that mechanical arm admittance is increased by the PASAT condition on a frequency range of 1.4 - 2.5 Hz. It reveals that the neuromuscular condition of the driver can be affected by distraction if the mental load of the driver is high and disturb the steering operation of the driver. However, it can be observed in the subfigure 45.b that the concerned participants were not affected by the proposed distraction method as they could maintain the same level of arm stiffness that leads to a similar amplitude of mechanical arm admittance for both NORMAL and PASAT stages. This indicates that the mental load required to perturb the driver depends on the mental capacities of each participants.



a- Averaged amplitude of mechanical arm admittance of distracted subjects



b- Average amplitude of mechanical arm admittance of non-distracted subject

Figure 45. Average amplitude of MAA for distracted drivers (a) and non-distracted drivers (b).

To determine whether distraction has a statistical impact on the amplitude of mechanical arm admittance, a two-way ANOVA with repeated measures was performed for the analysis of variance. This analysis concerned the subjects Nos. 3, 5, 8 and 9 since they are supposedly distracted. Two independent variables, which are the condition of the test (PASAT and NORMAL) and the frequencies before the cut-off frequency (0.5, 0.64, 0.83, 1.07, 1.39, 1.79 and 2.3 Hz), were used for the statistical analysis. Beforehand, assumptions were verified as there were no outliers, as assessed by examination of studentized residuals for values greater then +/-3, mechanical arm admittance amplitude was normally distributed, as assessed by Shapiro-Wilk's test of normality on the studentized residuals ($p > 0.05$). Mauchly's test of sphericity did not show any violation of sphericity. It was found that a significant two-way interaction exists between the conditions of the drivers and the frequencies before the cut-off frequency: $p = 0.000 < 0.05$, F (6, 66) = 6.891. Post hoc comparisons using F-Test with Bonferroni correction that concerns the variations in amplitude of mechanical arm admittance gain is presented in Table 6.

It can be observed in the Table 6 that the amplitude of mechanical arm admittance becomes significantly different after 1 Hz until 2.3 Hz, which is the cut-off frequency of the FRF of the driver. It indicates that distraction significantly increase the amplitude of mechanical arm admittance on a frequency range of 1.4 – 2.3 Hz.

Table 6. Report of single main effect of frequency on the variations in amplitude of mechanical arm admittance.

Frequency	*p*-value	*F*-value	Mean difference
0.5 Hz	0.810	$F(1, 11) = 0.061$	0.002
0.64 Hz	0.277	$F(1, 11) = 1.305$	-0.010
0.83 Hz	0.979	$F(1, 11) = 0.001$	0.000
1.07 Hz	0.104	$F(1, 11) = 3.138$	-0.019
1.39 Hz	0.000	$F(1, 11) = 41.927$	-0.054
1.79 Hz	0.000	$F(1, 11) = 61.274$	-0.065
2.3 Hz	0.030	$F(1, 11) = 6.159$	-0.037

In the following paragraph, a discussion on the impact of cognitive distraction on mechanical arm admittance is presented. It was observed in the previous section that the amplitude of mechanical arm admittance present two patterns. Indeed, some participants could be distracted sufficiently to present a difference in amplitude of mechanical arm admittance. In our experiment, the distraction method used in this experiment, which consists in a series of mathematical operation called PASAT presented in the Figure 24, was efficient for distracting the participants Nos. 3, 5, 8 and 9. For these participants, a difference in the amplitude of mechanical arm admittance on a frequency range of 1.4 – 2.3 Hz is observed in subfigure 45.a. This difference is statistically significant as it can be observed in Table 6 that report the single main effect of frequency of the concerned participants. This difference, which depends on the frequency range, is explained by the nature of the influence of cognitive distraction on the neuromuscular condition of the driver. Indeed, distraction increases the mental workload of the driver to a point where it is difficult to handle multiple tasks. In our experiment, distracted drivers had difficulty to answer correctly to the PASAT test and handle correctly the steering perturbations at the same time. It resulted in an incapacity to resist to the steering perturbation with specific frequency characteristics. Indeed, for lower frequencies of steering perturbations, distracted drivers could handle correctly the steering perturbations since the reflexive aspect of the neuromuscular condition of the driver can deal with low frequency steering perturbation but have more difficulty to adjust to higher frequencies steering perturbations. Indeed, P. van Drunen et al. reviewed that the reflexive neuromuscular condition is effective to react to steering perturbation before 1.1 Hz that explain the similarity of amplitude of mechanical arm admittance below 1.1 Hz in subfigure 45.a [75]. However, after 1.1 Hz, the reflexive neuromuscular mechanics is not sufficient to diminish the influence of steering perturbation as higher frequency steering perturbation does not stimulate the reflexive neuromuscular mechanics, which lead to a different in steering feedbacks of the driver to steering perturbations and consequently to a difference in amplitude of mechanical arm admittance.

As a result, distraction has a negative effect on the driver, relaxing them on a frequency range of [1.4 – 2.3] Hz. Out of this range, the capacity of drivers to resists to perturbation is similar. Moreover, it can be said that distraction is affecting consistently drivers since the driver perturb by the PASAT test show similar results for the three trials of the two stages of the experiment, i.e. PASAT and NORMAL. This review is also consistent the non-distracted participants since they showed no differences in amplitude of mechanical arm admittance during the three trials of the two stages of the experiment. In the following paragraph a conclusion is made on the content of this section.

In this study, the effects of distraction on mechanical arm admittance was investigated in the frequency domain where human power is dominant for steering operation. Participants performed a position task to estimate the mechanical arm admittance at two different occasions, in distracted and normal states. Mechanical arm admittance was estimated and its variations in gain were reviewed. There is a difference in the gain of mechanical arm admittance in the frequency range of 1.4 – 2.3 Hz. In this spectrum, the mechanical arm admittance of distracted drivers is higher in gain, which shows their reduced attention on the driving task as well as more relaxed driving. Outside this bandwidth, participants react similarly to steering perturbations because of the frequency limitations of arm responses.

5.2.3 Results: The impact of impaired condition on driving performances

In the following paragraph, the results that concern the variation of driving performance of the experiment presented in the section 4.3.1. are introduced.

The evolution of the average value of SRR of participants, as a function of the gap size is presented in the Figure 46. It can be observed that the SRR of alert drivers decreases quickly with the increase of the gap size compared to the SRR of drowsy drivers. Moreover, average of SDLP values was computed for both drowsy and alert stage, which can be observed in the Figure 47.

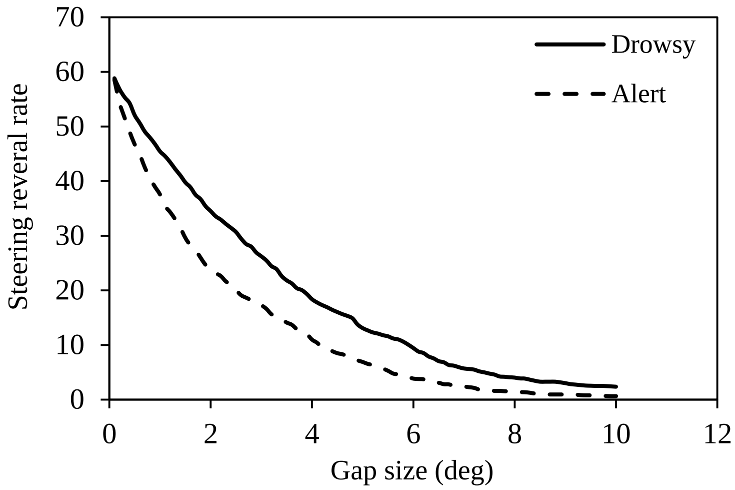


Figure 46. Average steering reversal rate with the increase of the gap size.

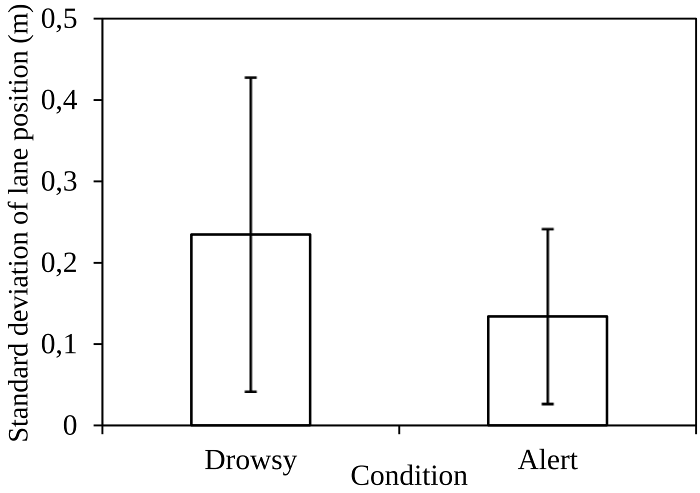
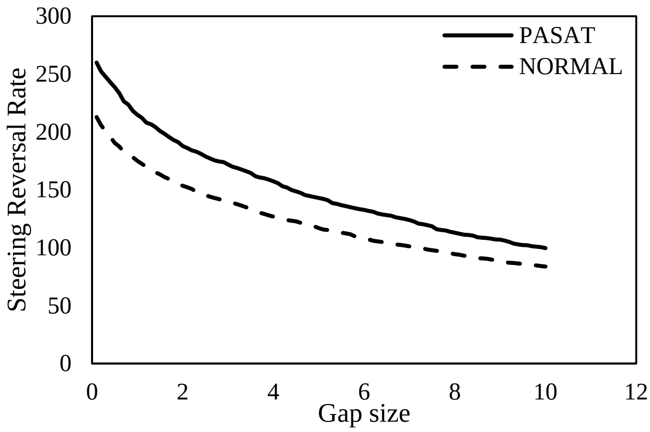


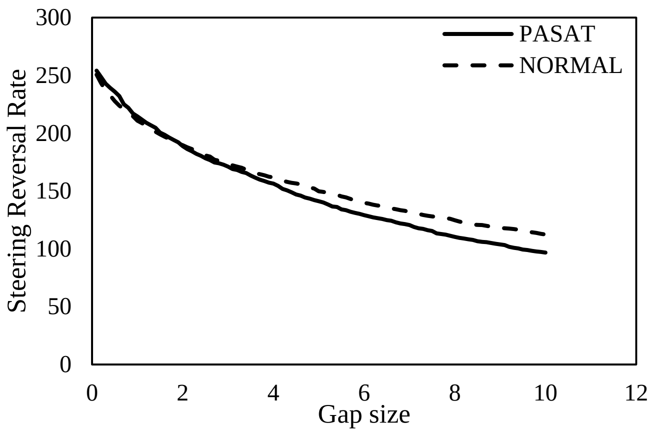
Figure 47. Average SDLP values between drowsy and alert states.

It can be observed that the average amplitude of SDLP is increased by drowsiness. An increase in SDLP value implies a decrease in driving performance. It was in this study that the average value of the SDLP increase by of 0.10 meters between the alert and drowsy states. To determine if drowsiness has statistical impact on the value of SDLP, a one-way ANOVA with repeated measures was performed. However, the report does not appear to be sufficiently significant: $p = 0.133$, $F(1, 9) = 2.733$. The reason of the high variability in SDLP values for drowsy drivers is caused by the difference in the effects of drowsiness on drivers that leads to inconsistent lateral position of the vehicle. In the following paragraph, the results that concern the variation of driving performance of the experiment presented in the section 4.3.2. are introduced.

The evolution of the average value of SRR of participants, as a function of the gap size is presented in the Figure 48.



a- Average SRR between NORMAL and PASAT stage of distracted driver (Subjects Nos. 3, 5, 8 and 9).



b- Average SRR between NORMAL and PASAT stage of non-distracted driver (Subjects Nos. 1, 2, 4, 6, 7 and 10).

Figure 48. Average SRR of NORMAL and PASAT stages for distracted (a) and non-distracted (b) subjects.

It can be observed in the subfigure 48.a that the number of steering occurrence is higher for distracted subjects. Higher value of SRR indicates an increased number of steering reversal, which demonstrate an instability to control the steering wheel with stability. As a result, the distracted drivers tend to perform more steering operation in order to adjust the trajectory of the car since they cannot focus on providing a smooth control of the steering wheel because of the induced distraction that increase the mental workload of the driver. Moreover, it can be observed in subfigure 48.b that total number of steering operations performed by driver is similar but quicker with the introduction of the PASAT test. Indeed, with the introduction of PASAT, the participants tend to show less steering operation with the increase of the gap size, which indicate an improved control of the vehicle. Furthermore, average of SDLP values was computed for both PASAT and NORMAL stages, which can be observed in the Figure 49.

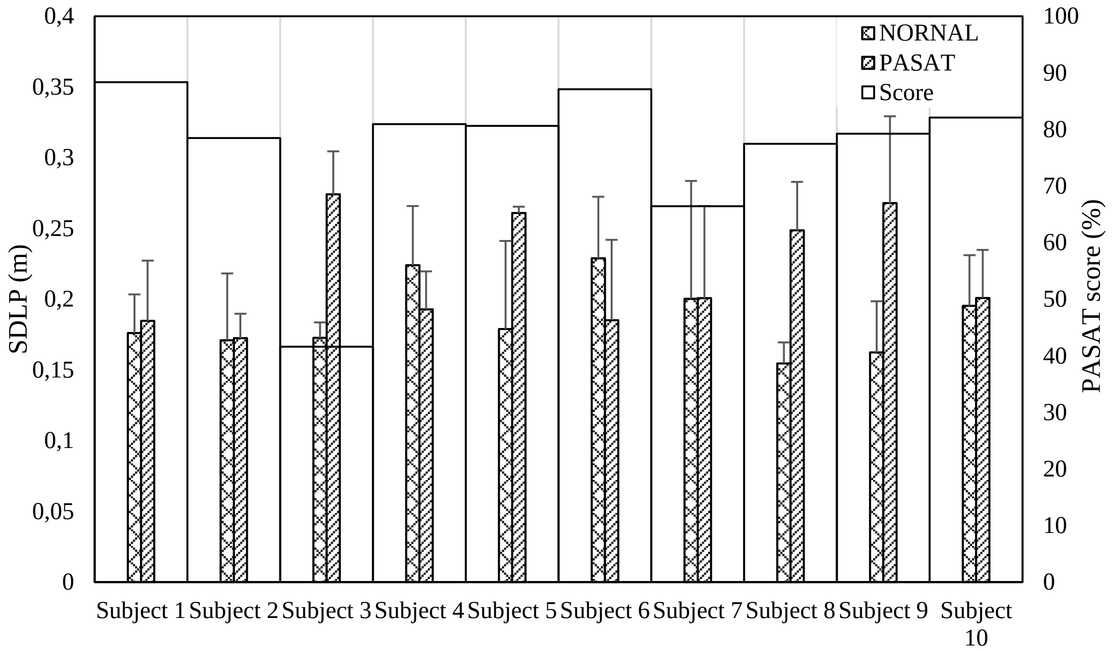


Figure 49. Average SDLP values between PASAT and NORMAL stages for each participant.

It can be observed in the Figure 49 that the average SDLP value is higher for Subject Nos. 3, 5, 8 and 9 while performing PASAT stage. These review is consistent with the review done in section 4.4.2, in which we reviewed an increase of mechanical arm admittance for the same subjects on a specific frequency range. The value of SDLP of other subject is the similar between the PASAT and NORMAL stages.

To determine whether distraction has a statistical impact on the value of SDLP, a one-way ANOVA with repeated measures was performed for the analysis of variance. This analysis concerned the subjects Nos. 3, 5, 8 and 9 since they are supposedly distracted. Beforehand, assumptions were verified as there were no outliers, as assessed by examination of studentized residuals for values greater then +/- 3, mechanical arm admittance amplitude was normally distributed, as assessed by Shapiro-Wilk's test of normality on the studentized residuals ($p > 0.05$). Mauchly's test of sphericity did not show any violation of sphericity.

It was found that the value of SDLP were significantly different for distracted drivers between the NORMAL and PASAT stages: $p = 0.000 < 0.05$, $F\ (1, 11) = 109.603$. This result indicate that distraction has an influence on the lane keeping, increasing lateral deviation of the vehicle when the driver is distracted. In the following paragraph, a discussion on the impact of drowsiness driving performances is presented.

Driving performances variations between drowsy and alert states were estimated via the computation of SRR and SDLP. The tendency observed in the Figure 46 shows that the steering reversal occurrence is similar for both drowsy and alert drivers. However, it quickly changes with the increase of the gap size. Indeed, the steering reversal rate among alert drivers decreases faster compared to that of drowsy drivers. It expresses that steering operation amplitudes of drowsy drivers are larger. This means that alert drivers can minimize steering wheel angle variations caused by steering perturbations better than drowsy drivers, denoting an increase of risky steering behavior among drowsy drivers. The SDLP was also computed and can be observed in the Figure 47. It is suggested in the literature that large SDLP values often imply a high probability of lane departure [6]. Most studies that use SDLP agree on the reliability of this measure for assessing the effects of drowsiness on participants [54][76]. In our experiment, it was found an increase in SDLP values of 0.10 in average between the alert and drowsy states. However, this difference was not significant but the high variability of SDLP for drowsy driver expresses that drowsy drivers are in the incapacity to maintain a stable lateral position. It shows that drowsiness has various effects on driving of participants, which is the consequence of the variety of drivers in their capacities to react to steering perturbations. This review was also done by Wylie et al [77].

According to our results, driving performances evaluated by the steering reversal rate and the standard deviation of lane position were negatively impacted by drowsiness as it induces reduction of awareness and impaired driving, which is also reviewed by other studies that investigate the effects of drowsiness on driving performances [9][52][58]. In the following paragraph, a discussion on the impact of cognitive distraction on driving performances is presented.

Driving performances variations between drowsy and alert states were estimated via the computation of SRR and SDLP. The tendency observed in subfigure 48.a demonstrated that the number of steering operation is increased by distraction as the SRR of distracted driver is higher than non-distracted driver, independently from the gap size. This means that drivers presenting a normal condition can minimize steering wheel angle variations caused by steering perturbations better than distracted drivers. This indicates that the driver cannot adjust properly the operation required for controlling of steering wheel, which is consistent with the review of Marrkula et al. [78]. Moreover, the SDLP was computed and is presented in the Figure 49. The score of the PASAT test is also presented in the same figure. It can be observed that Subject Nos 3, 5, 8 and 9 present higher SDLP value during the PASAT stage compared to the NORMAL stages, which is coherent with the results of section 4.4.2, in which the same participants presented an increase in amplitude of mechanical arm admittance on a specific frequency range, leading to a decreased capacity to resist to steering perturbation. This decrease leads consequently in a decrease of the steering wheel control quality and to an increase of the SDLP during the PASAT stage. Moreover, it can be observed in the Figure 49 that the score of the PASAT test is not affecting the inducement of distraction since the subject 3 performed poorly the PASAT test (less than 50% of correct answer) but was still distracted by this task. For this subject, performing the PASAT test and steering operations at the same time was very complicated and induced very high mental workload. In the following paragraph a conclusion is made on the content of this section.

The effect of impaired condition on the driving performances was assessed by the comparison of the SDLP values and SRR variation between normal and impaired condition. The tested impaired condition are drowsiness and distraction. This study leads to the following conclusion concerning the variations in amplitude of mechanical arm admittance

1. Drowsiness has negative effects on driving performances, increasing the amplitude of steering operations as assessed by the variations of SRR, and leading to higher lateral deviation of the vehicle.
2. Distraction has negative effects on driving performances, increasing the amplitude of steering operations as assessed by the variations of SRR, and leading to higher lateral deviation of the vehicle.

5.3. Haptic steering guidance to influence the neuromuscular condition of the driver

5.3.1. Results: The enhancement of the NMS condition of the driver using haptic steering guidance

In this section, the results of the experiment presented in the section 4.4.1. are introduced.

In following, the estimation of the average amplitudes of mechanical arm admittance is presented. The phase graph of the estimations of mechanical arm admittance of this study can be observed in Appendix.

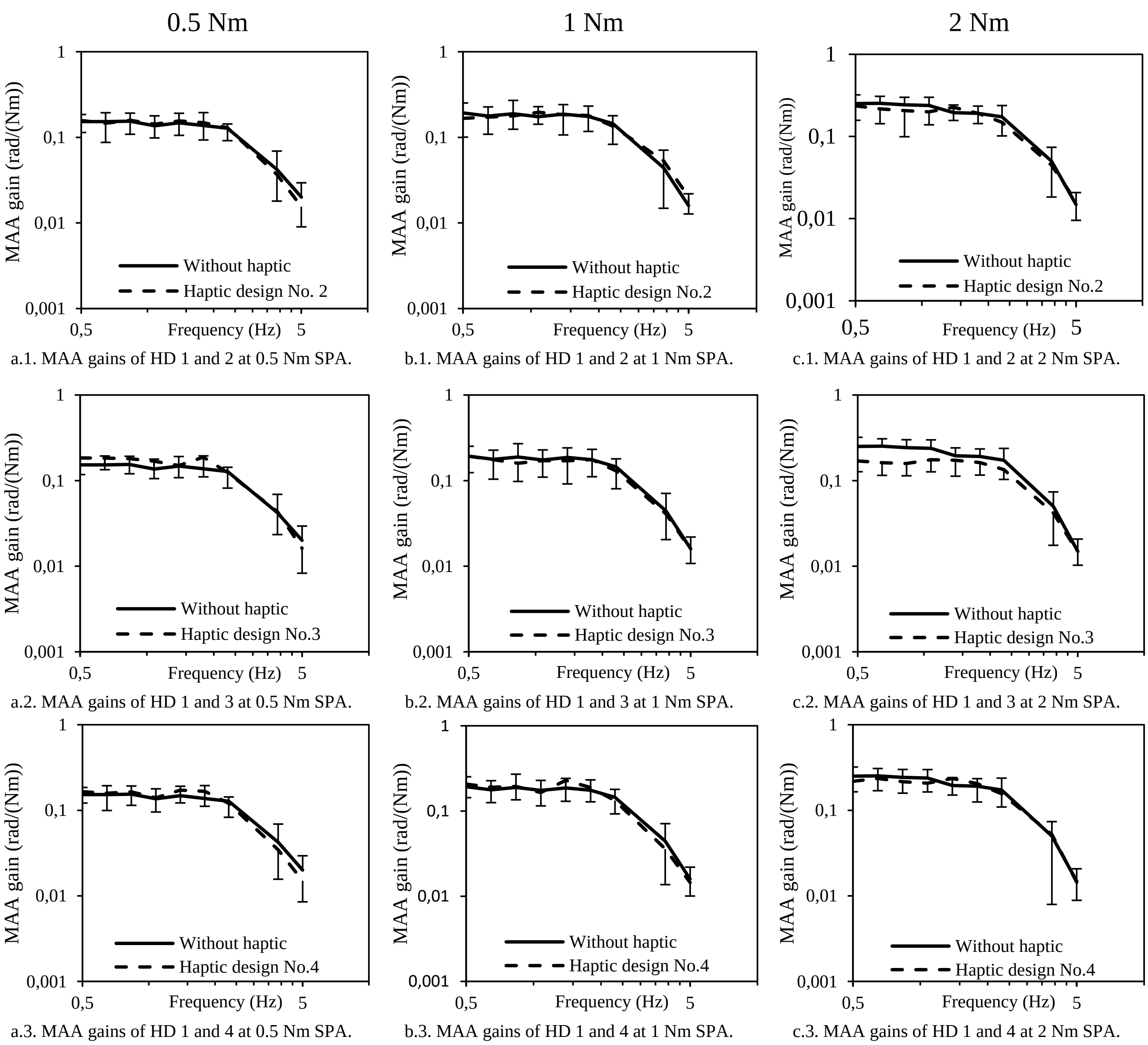
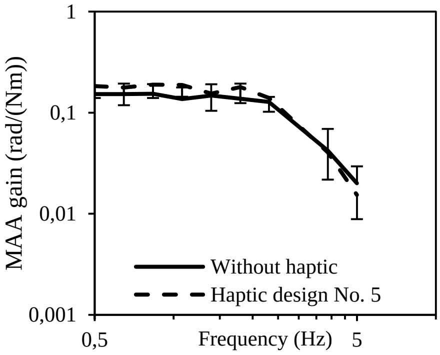
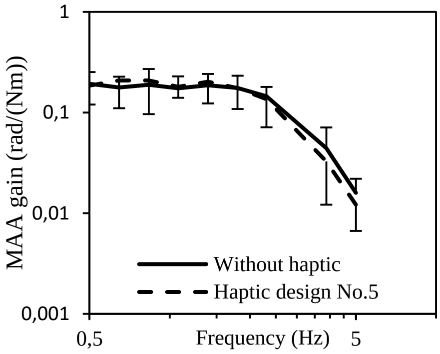


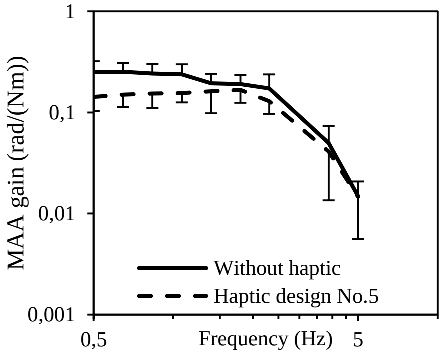
Figure 50.a. Comparison of mean mechanical arm admittance gain corresponding to amplitude of steering perturbation (a–c) and level of haptic assistance (2–8).



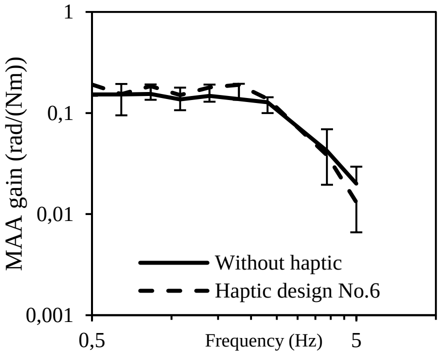
a.4. MAA gains of HD 1 and 5 at 0.5 Nm SPA.



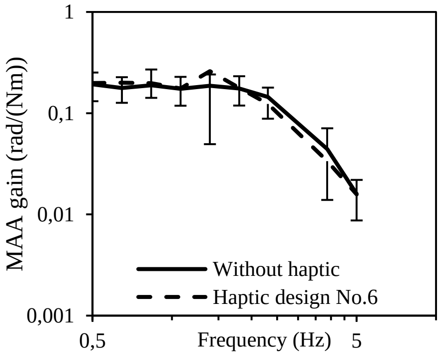
b.4. MAA gains of HD 1 and 5 at 1 Nm SPA.



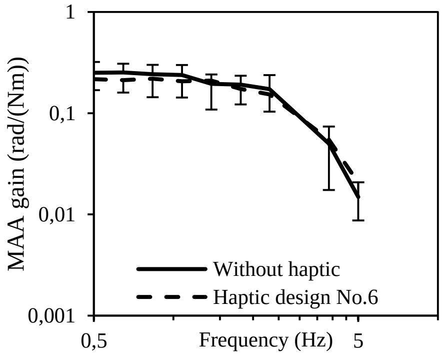
c.4. MAA gains of HD 1 and 5 at 2 Nm SPA.



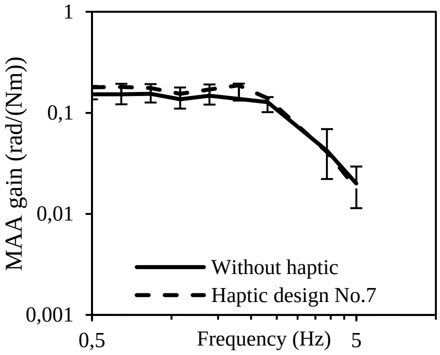
a.5. MAA gains of HD 1 and 6 at 0.5 Nm SPA.



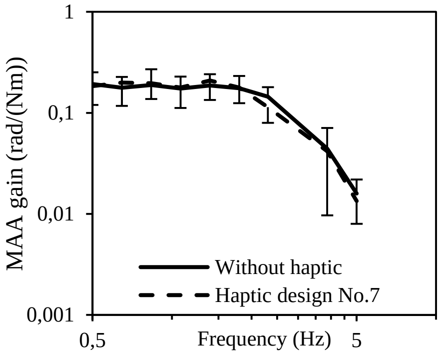
b.5. MAA gains of HD 1 and 6 at 1 Nm SPA.



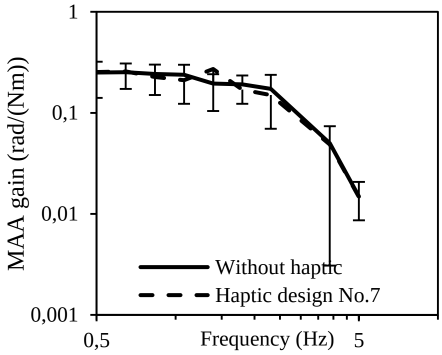
c.5. MAA gains of HD 1 and 6 at 2 Nm SPA.



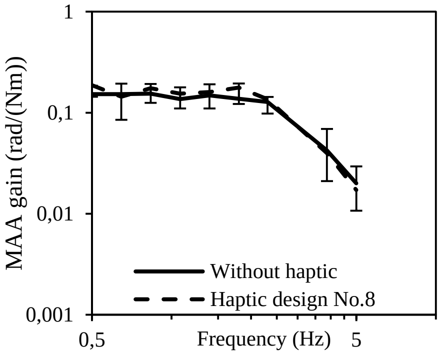
a.6. MAA gains of HD 1 and 7 at 0.5 Nm SPA.



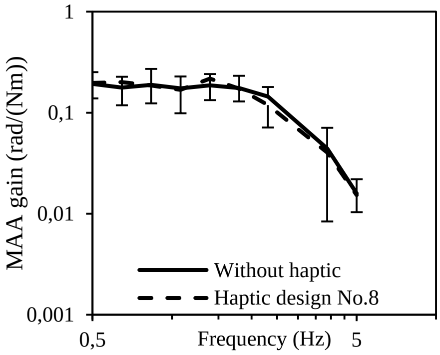
b.6. MAA gains of HD 1 and 7 at 1 Nm SPA.



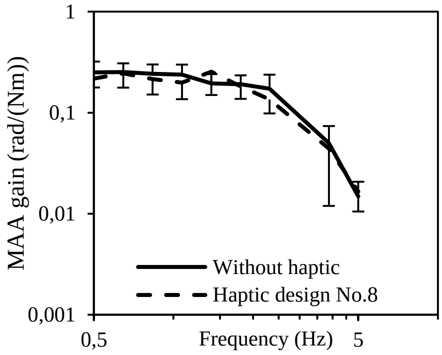
c.6. MAA gains of HD 1 and 7 at 2 Nm SPA.



a.7. MAA gains of HD 1 and 8 at 0.5 Nm SPA.



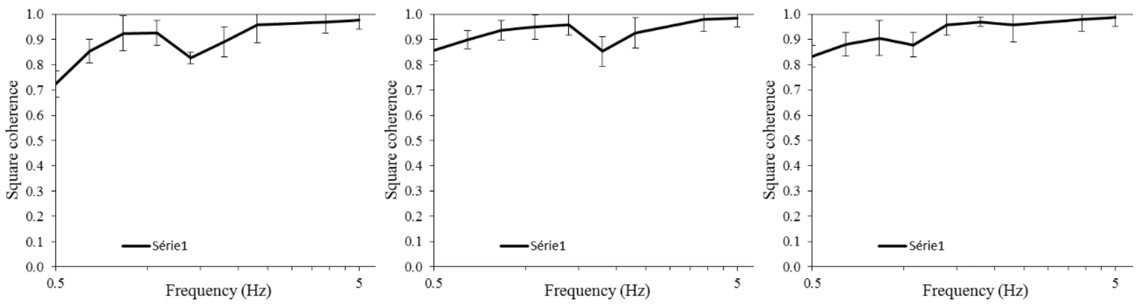
b.7. MAA gains of HD 1 and 8 at 1 Nm SPA.



c.7. MAA gains of HD 1 and 8 at 2 Nm SPA.

Figure 50.b. Comparison of mean mechanical arm admittance gain corresponding to amplitude of steering perturbation (a–c) and level of haptic assistance (2–8).

In the Figure 51, the squared coherence of mechanical arm admittance is presented and represent the reliability of the estimation of the neuromuscular condition of the driver. It is confirmed the squared coherence are superior than 0.5, which is used as a confirmation for the understanding of the amplitude of mechanical arm admittance.



0.5 Nm steering perturbation amplitude   1 Nm steering perturbation amplitude   2 Nm steering perturbation amplitude

Figure 51. Coherence of mechanical arm admittance.

To determine whether haptic steering guidance design has a statistical impact on standard deviation of lane position, a two-way ANOVA with repeated measures was performed for the analysis of variance. Two independent variables, which are the amplitude of steering perturbations and the type of haptic design, were used for the analysis of variations of amplitude of mechanical arm admittance. It was found that a significant two-way interaction exists between the amplitude of steering perturbations and the type of haptic design: $F(14,1358) = 13.747$, $p = 0.00 < 0.05$. Post hoc comparisons using F-Test with Bonferroni correction that concerns haptic steering guidance at 0.5 Nm showed a statistically significant difference in mechanical arm admittance amplitudes between trials, $F(1, 97) = 17.727$, $p = 0.000$; at 1 Nm, did not show any statistically significant differences in mechanical arm admittance amplitude s between trials, $F(1,97) = 1.382$, $p = 0.243$; at 2 Nm, did not show any statistically significant difference in mechanical arm admittance amplitudes between trials, $F(1, 97) = 0.158$, $p = 0.692$.

Table 7. Pairwise comparison results of different trials without haptic steering guidance (HD 1) with trials with haptic steering guidance (HD 2 - 8).

Haptic Design No.	Low – 0.5 Nm		Medium – 1 Nm		High – 2 Nm	
	p-value	Mean diff	p-value	Mean diff	p-value	Mean diff
2	1.000	-0.004	1.000	0.004	0.833	0.018
3	0.006	-0.025	1.000	0.009	0	0.059
4	1.000	-0.01	1.000	-0.011	1.000	0.011
5	0.002	-0.029	1.000	-0.009	0	0.069
6	0.07	-0.023	1.000	-0.015	0.173	0.022
7	0.014	-0.025	1.000	-0.004	1.000	0.004
8	0.28	-0.017	1.000	-0.004	1.000	0.013

As it can be observed in Table 7, which presents the pairwise comparison, coupled with the p-values, of mechanical arm admittance amplitudes of trials where the different designs of haptic steering guidance were applied to the steering wheel in comparison to the ones without haptic steering guidance, the mechanical arm admittance amplitude is significantly decrease by the application of haptic steering guidance for certain types of haptic steering guidance design at corresponding steering perturbation amplitudes. This was performed to differentiate the steering perturbation amplitude from the haptic design.

For low steering perturbation amplitude, i.e. 0.5 Nm, significant differences were found for haptic designs No. 5 and a near-significant difference was found for designs No. 3 and 6. For medium steering perturbation amplitude, i.e. 1 Nm, no significant differences were found. For high steering perturbation amplitude, i.e. 2 Nm, significant differences were found for haptic steering guidance design Nos. 3 and 5. Moreover, the mean difference of mechanical arm admittance amplitude shows interesting features, depending on the steering perturbation amplitude. Indeed, for low steering perturbation amplitude, the mean difference is negative, which means that mechanical arm admittance amplitude was increased by haptic steering guidance, which expresses a relax driving facing steering perturbations. For high steering perturbation amplitude, the mean difference is positive, which means that mechanical arm admittance amplitude was decreased by haptic steering guidance Nos. 3 and 5, which express a tensed driving facing steering perturbations. The haptic designs Nos. 3 and 5 correspond to the focus on the a_4 coefficient of the equation (15), which corresponds to the monitoring of the yaw rate. Moreover, increase in the a_4 coefficient increases the mean difference in the amplitude of mechanical arm admittance. Indeed, the a_4 coefficient of haptic design No. 5 is higher than the a_4 coefficient of haptic design No. 3. Consequently, haptic design No. 5 decreases more the amplitude of mechanical arm admittance compared to haptic design No. 3. This review expresses that haptic steering guidance is effective at high steering perturbation amplitudes for torque feedback that monitor the yaw rate of the vehicle. If so, the amplitude of mechanical arm admittance is decreased, revealing an increase in the stiffness of the arm. The conclusion of this statistical analysis is that haptic steering guidance increases mechanical arm admittance at low steering perturbation amplitude and decreases mechanical arm admittance amplitude for specific designs of haptic steering guidance that focus on the monitoring of the yaw rate of the vehicle. In the following paragraph, a discussion on the optimal design of haptic steering guidance to enhance the neuromuscular condition of the driver is presented.

In this experiment, the influence of the design of haptic steering guidance combined with various amplitudes of steering perturbation on mechanical arm admittance of participants was investigated. The different design of haptic steering guidance focused on the monitoring of coefficients that control the yaw angle and the yaw rate of the vehicle. A trial without haptic steering guidance was experienced to build a baseline to highlight the effects of the design of haptic steering guidance on mechanical arm admittance for each amplitude of steering perturbation. The results displayed in the Figure 50 show that haptic steering guidance is effective in decreasing the amplitude of mechanical arm admittance for specific haptic steering guidance designs and steering perturbation amplitude.

For high amplitude of steering perturbations, remarkable differences in amplitudes of mechanical arm admittance are observable with haptic designs Nos. 3 and 5 as it can be observed in statistical results of Table 7. These designs focus on monitoring the a_4 coefficient. This coefficient affects the steering feedbacks that impact the yaw rate of the vehicle. Monitoring the a_4 coefficient permits the system to counter the acceleration caused by steering perturbations. The influence of other coefficients a_1, a_2 and a_3, which control the lateral error, the lateral velocity and the yaw angle of the vehicle, is negligible.

Furthermore, the reaction of drivers to steering perturbation was also subjected to the self-aligning torque, which is produced by the reaction of the road on the tires while steering. The advantage of using haptic steering guidance control based on yaw angle feedbacks, among others, is that it decreases the influences of the self-aligning torque as it acts on the same variables. Thus, it might change the driving experience. Whereas, the amplitude of the self-aligning torque in comparison to the amplitude of the steering perturbation is minimal and consequently do not affect the validity of the results. Moreover, the self-aligning torque is usually felt by the driver while steering in a curve, but, in our experiment, drivers perform the scenario on a straight road, which diminish the difference in driving sensation emitted in the previous sentences.

Additionally, the difference in amplitude of mechanical arm admittance tend to increase with increase in value of the a_4 coefficient as it can be noticed in the mean difference in Table 7 and the corresponding haptic designs presented in Table 6. With respect to these designs, haptic steering guidance is beneficial to drivers, leading to an increase of the muscle activation of drivers, which induces a tight driving technique. High amplitude of steering perturbation makes the control of the steering wheel challenging, and drivers cannot efficiently counter steering perturbations. Consequently, haptic steering guidance becomes an effective way to help drivers and decreases the driving burden.

For medium amplitude of steering perturbation, i.e. 1 Nm, the haptic steering guidance designs do not impact the amplitude of mechanical arm admittance. This result indicates that haptic steering guidance does not impact driver behaviour. Moreover, this review expresses that 1 Nm is the optimal perturbation amplitude that drivers can counter without assistance. Consequently, drivers can maximize the use of their physical capacities and can minimize the influence of 1 Nm steering perturbations efficiently.

For low steering perturbation amplitudes, i.e. 0.5 Nm, the haptic steering guidance designs increase the amplitude of mechanical arm admittance. The easiness of the steering task makes the influence of steering acceleration negligible. In this condition, the steering task is effortless, and haptic steering guidance makes the task even easier. This result explains why drivers become relaxed, whatever the type of haptic design is present in the assistance system. Indeed, the mean differences observed in Table 7. present an increase in mechanical arm admittance that expresses a relaxation of drivers.

As a result, monitoring the yaw rate coefficient at high amplitude of steering perturbation highlights to be efficient to increase the arm stiffness of drivers and focus on the driving tasks. The efficiency of yaw rate coefficient monitoring supports the conclusions from the review by Güvenc et al. concerning the design of haptic steering guidance [65]. They designed a steering controller based on disturbance control by drivers and vehicle yaw dynamics improvement, which showed robust performance. Haptic feedback based on yaw angle monitoring is adequate compared with the control of lateral position. Indeed, steering angle amplitude variations are more important compared with the lateral deviation of the vehicle.

Moreover, Russel et al. demonstrated that the monitoring of the yaw rate is essential for the control of the vehicle choice because it better maintains the overall emulation performance [79]. Indeed, it is important to keep the vehicle turning in the same direction as the driver is steering, which is easily achieved by tracking the yaw rate. In case the haptic steering guidance focuses on the lateral velocity, the uncontrolled yaw rate can actually go the opposite direction as the driver's command, which is very disconcerting for the which can lead to substantial mistakes concerning the understanding of the intentions of the driver.

Moreover, steering feedbacks are mostly based on the derivative of measured variables for both the rotational and translational controllers [80]. For example, if a measured variable of a translational controller is the position, the feedback is often made on the speed. Moreover, if the measured variable of a rotational controller is the angular speed, the feedback is often made on the angular acceleration. This explains why monitoring the a_4 coefficient, which affects the yaw rate, is an effective way to significantly decrease the mechanical arm admittance amplitude.

Furthermore, it can be observed from Figure 50 that haptic steering guidance is effective in reducing mechanical arm admittance in a specific frequency range at lower frequencies. Abbink et al. demonstrated that two mechanisms take part in arm behaviour: muscle co-contraction and reflexive stiffness [67]. The reflex activity is an efficient way to increase arm stiffness, and has a major influence on resistance to perturbations, but is limited to frequencies smaller than 3 Hz. This activity explains the convergence of mechanical arm admittance gain for frequencies larger than 3 Hz.

As a result, haptic steering guidance is an effective way to assist drivers and decrease their arm stiffness under the following conditions: first, the steering perturbations should be large enough in amplitude to significantly perturb drivers; second, haptic steering guidance design should monitor the yaw rate of the vehicle. In other cases, haptic steering guidance either does not affect driver behaviour, or even relax drivers. In the following paragraph a conclusion is made on the content of this section.

This study concentrates on the influence of haptic steering guidance on driving behaviour estimated through mechanical arm admittance. To achieve this target, a haptic steering guidance model was built and implemented in a driving simulator that can assist drivers to follow an ideal trajectory, with real-time steering feedback based on monitoring lateral error, yaw angle, and their various derivatives. The experimental results indicate that the arm stiffness of drivers, represented by mechanical arm admittance, depends on steering perturbation amplitude and haptic steering guidance design. The following points can be concluded from the experimental study:

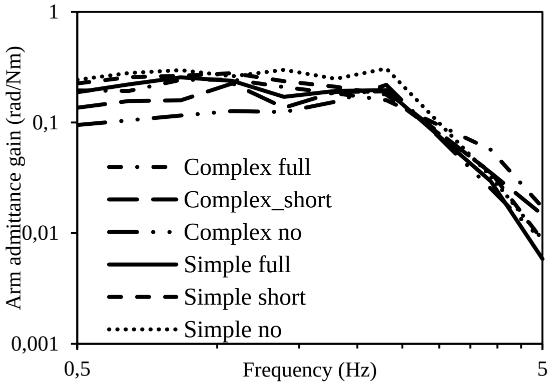
1. For a steering perturbation of 0.5-Nm amplitude, haptic steering guidance relaxes drivers, independent of the steering haptic design.
2. For a steering perturbation of 1-Nm amplitude, arm stiffness is not affected by haptic steering guidance, and driving operations are not affected by haptic steering guidance.
3. For a steering perturbation of 2-Nm amplitude, haptic steering guidance is effective in assisting the driver under specific haptic steering guidance designs. These designs focus on providing steering feedback according to the derivative of the vehicle yaw angle variation.

As a result, to construct an efficient haptic steering guidance system that can assist drivers, the haptic model that provides steering feedback should pay attention to the amplitude of steering perturbations and reduce the influence of the yaw rate.

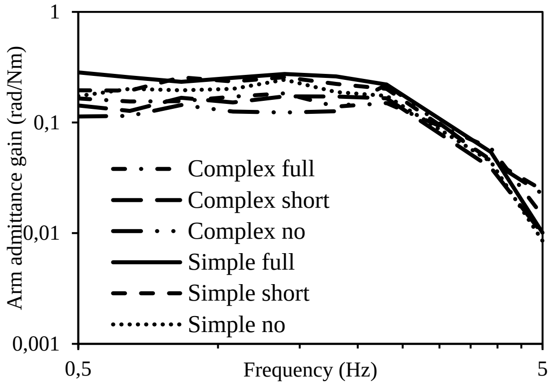
5.3.2. Results: Condition of application of haptic steering guidance to enhance the NMS of the driver

In this section, the results of the experiment presented in the section 4.4.2. are introduced.

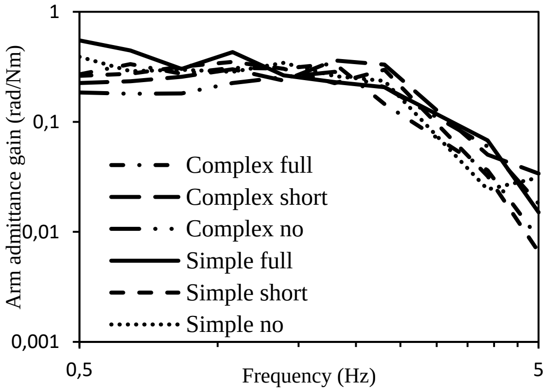
The amplitude of mechanical arm admittance for the different duration of haptic steering guidance, which are ‘full’, ‘Short’, and the two scenario difficulties, which are simple and complex, can be observed in the Figure 52. The phase of mechanical arm admittance of this study is presented in Appendix.



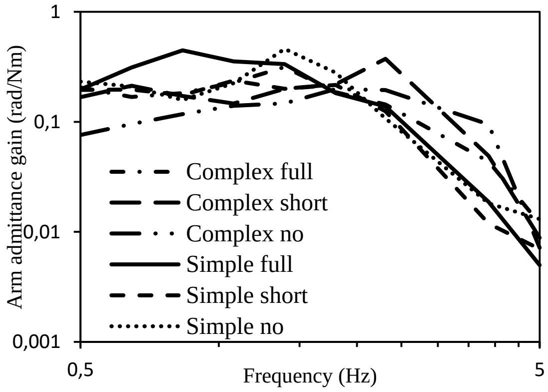
a. MAA of subject 1.



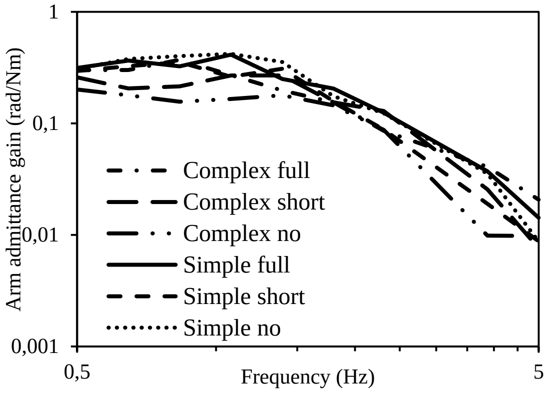
b. MAA of subject 2.



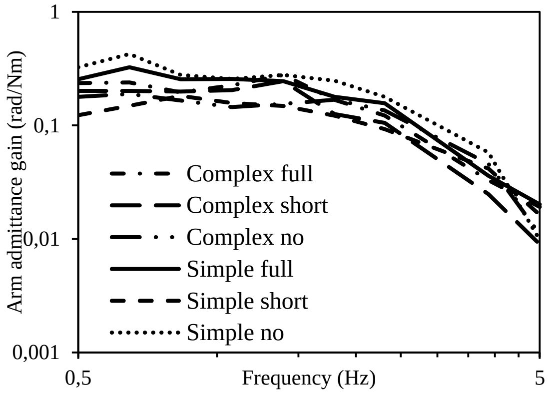
c. MAA of subject 3.



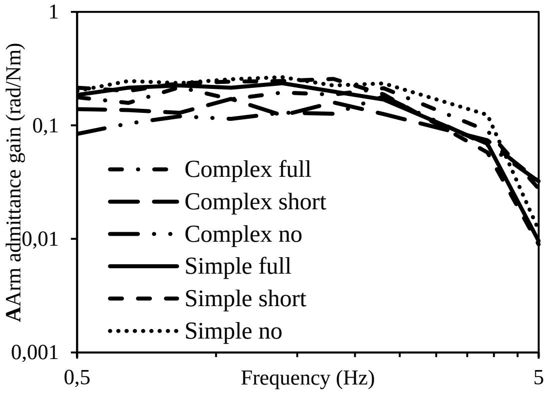
d. MAA of subject 4.



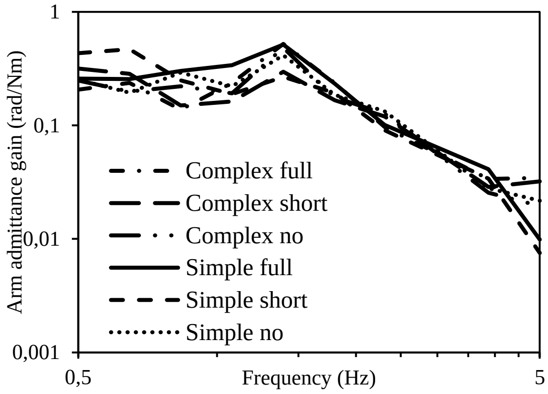
e. MAA of subject 5.



f. MAA of subject 6.

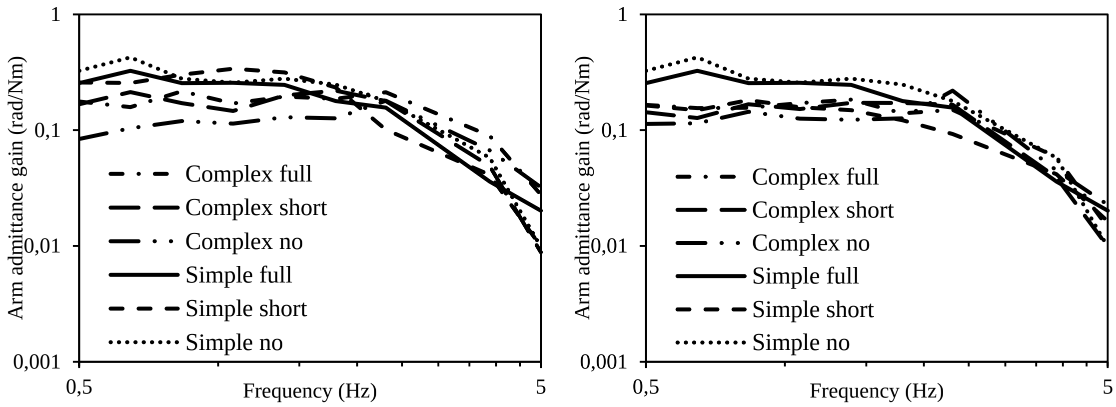


g. MAA of subject 7.



h. MAA of subject 8.

Figure 52.a. Amplitude of MAA for each participant depending on the complexity of the driving scenario and the duration of haptic steering guidance application during the conditioning task



i. MAA of subject 9.

j. MAA of subject 10.

Figure 52.b. Amplitude of MAA for each participant depending on the complexity of the driving scenario and the duration of haptic steering guidance application during the conditioning task.

It can be observed in the Figure 52 that amplitudes of mechanical arm admittance tend to be higher for simple driving condition. Moreover, it seems that the duration of application of haptic steering guidance feedbacks during the conditioning task affect the amplitude of mechanical arm admittance. In order to present the results of Figure 52 on the same graph, the average amplitude of mechanical arm admittance of all participants is presented in the Figure 53.

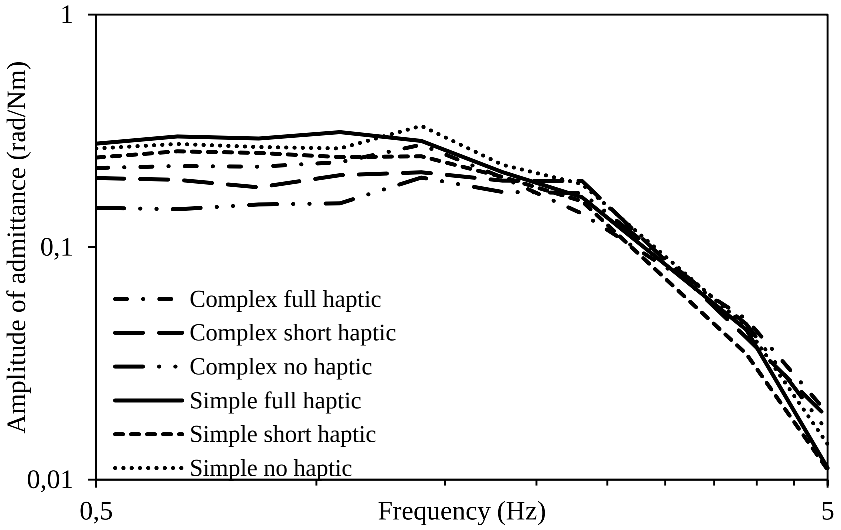


Figure 53. Average amplitude of mechanical arm admittance depending on the complexity of the driving scenario and the duration of haptic steering guidance application during the conditioning task.

It can be observed that the application of haptic steering guidance has different effect on the amplitude of mechanical arm admittance before the cut-off frequency, which depends on the difficulty of the scenario. For the complex driving scenario, it can be observed in the Figure 53 that the amplitude of mechanical arm admittance is increased by the duration of haptic steering guidance application. It implies that the duration of haptic steering guidance decreases arm stiffness and consequently relaxes drivers. For the simple driving scenario, it can be observed in the Figure 53 that the amplitude of mechanical arm admittance is not impacted by the duration of haptic steering guidance since a clear tendency cannot be observed. Moreover, it can be observed that mechanical arm admittance amplitudes are higher in the simple scenario, which means that drivers are more tensed when they have to perform complex steering tasks. After the cut off frequency, amplitudes of mechanical arm admittance for both scenarios and their respective haptic duration are similar.

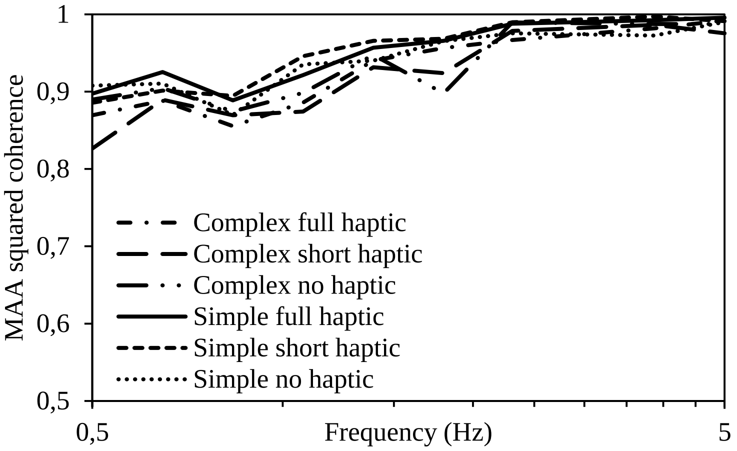


Figure 54. Coherence of mechanical arm admittance.

To determine whether the duration of haptic steering guidance duration has an impact on mechanical arm admittance amplitude, we performed a repeated measure, two-way analysis of variance (ANOVA) across the relevant trials. This analysis was performed about the variations of amplitude of mechanical arm admittance before the cutoff frequency. Beforehand, assumptions were verified as there were no outliers, as assessed by examination of studentized residuals for values greater then +/- 3, mechanical arm admittance amplitude was normally distributed, as assessed by Shapiro-Wilk's test of normality on the studentized residuals ($p > 0.05$). Mauchly's test of sphericity did not show any violation of sphericity. Two independent variables, which are the difficulty of the steering task and the duration of haptic steering guidance application, were used for the analysis of variations of the amplitude of mechanical arm admittance before the cut-off frequency. A significant interaction was found between steering difficulty and haptic duration; $p = 0.000$, $F(2,138) = 19.344$. We decided to present multiple comparison results of those trials that caught our interest, i.e. without-haptic condition and with-haptic condition, for both the simple and complex scenarios. The single main effect report about the difference in amplitude of mechanical arm admittance expressed that the amplitudes of mechanical arm admittance is significantly increased by the application of haptic steering guidance for the complex scenario, $p = 0.000$, $F(1,69) = 63.416$ with a mean difference of 0.066 rad/Nm for the application of long term application and $p = 0.000$, $F(1,69) = 33.647$ with a mean difference of 0.042 rad/Nm for the application of short term haptic steering guidance. Furthermore, there are not any significant differences in amplitudes of mechanical arm admittance for the simple driving scenario. In the following paragraph, a discussion on the duration of application of haptic steering guidance depending on the driving complexity to enhance the neuromuscular condition of the driver is presented.

In this experiment, the influence of the duration of haptic steering guidance application on the driver state was evaluated. This influence was reviewed according to the nature of the steering task, which are simple and complex. Mechanical arm admittance was computed and used as an indicator of the state of the driver. It can be observed in the Figure 53 that the amplitude of mechanical arm admittance during simple driving stages are greater than amplitudes of mechanical arm admittance during complex driving stages, implying that neuromuscular conditions have an influence on mechanical arm admittance amplitude. During simple scenario, some drivers positioned their hands on the steering wheel in an "8 to 4” position, expressing a relaxed hand position, which is confirmed by higher amplitudes of mechanical arm admittance. This review expresses that the difficulty of the steering task is an important factor for the design of haptic steering guidance system, since differences in behaviour of the drivers are observed. The analysis in this study was then divided according to the difficulty of the steering task.

In complex driving conditions, the statistical analysis, which is presented in section 4.3 confirm that applying haptic steering guidance significantly increases the amplitude of mechanical arm admittance as it can be observed in the Figure 48, which its meaning is that haptic steering guidance relaxes participants. This review was examined for both full and short-term application of haptic steering guidance and present higher relaxation as the duration of the application of haptic steering guidance increases. Participants tend to rely on the assistance provided because it facilitates steering operations. A similar review has been done by Lee et al. [26]. Physiological explanation of these reviews lies in arm muscle co-contraction. Arm muscle co-contraction decreases thank to the steering assistance provided by haptic steering guidance, which induces a relaxed driving. Initially, non-assisted drivers may co-contract muscles to compensate driving difficulties and to ensure robust control of their trajectory. Indeed, previous research also assessed considerable muscle co-contraction when drivers generated large steering angles to complete lane change manoeuvres, which also resemble to steering operation during curves [81]. For assisted-drivers, haptic steering guidance takes this role. It can be observed in the Figure 53 that differences in amplitudes of mechanical arm admittance are located before the cut-off frequency. This phenomenon can be explained by the physiological properties of the arm, which its reflex activity is powerful, but limited to frequencies below 3 Hz [67].

As haptic steering guidance provides steering assistance, participants performing complex driving tasks can improve the quality of their lane-keeping. Indeed, Marchal-Crespo et al. reviewed that drivers could learn when to initiate sharp curves or when to straighten their trajectory after exiting a curve, with the aid of haptic steering guidance [23]. The concept that guidance can improve the learning of timing is also consistent with the results of Feygin et al. [82]. It may be acceptable to say that continuous haptic steering guidance application is a promising way to support drivers in actively producing optimal steering actions whilst driving in complex situations since it considerably enhances steering performance during the conditioning task but slightly increases trajectory deviations when steering perturbations occur, caused by the relaxation induced by haptic steering guidance application.

In simple driving conditions, applying haptic steering guidance does not have any effect on mechanical arm admittance amplitude since the steering task is simple enough to be handled efficiently by the driver alone. Results of the statistical analysis concerning mechanical arm admittance amplitude variations did not show any significant differences, and amplitude of mechanical arm admittance of Figure 53 does not show a clear trend.

Guidance benefited drivers in terms of learning how to handle curves properly, but not curves with large radii. Driving along a straight line requires small responses proportional to the tracking errors, compared with the large, precisely timed movements required for turning into curves and straightening during turn exiting [25]. To some extent, it also does not affect driving behaviour when participants enter high radius turns, which closely resemble straight lines as curvature increases. This review explains why haptic steering guidance does not affect both driving performances and mechanical arm admittance while performing a simple scenario. The simplicity of the scenario makes haptic steering guidance useless in assisting drivers and the muscle activity of participants was not affected by haptic steering guidance. Previous studies also reviewed a difference in muscle activity depending on the road geometry. Katzourakis et al. demonstrated that during curve taking, drivers increase arm stiffness compared with driving linearly [33]. These results are consistent in explaining differences in mechanical arm admittance amplitude for complex driving scenario and why this difference is absent for simple driving scenario. In the following paragraph a conclusion is made on the content of this section.

In this study, we investigated the after-effects of haptic steering guidance on mechanical arm admittance. In order to establish its influence depending on road conditions, two scenarios were made: a complex scenario that requires frequent operations on the steering wheel and a simple scenario that does not. Furthermore, two durations of haptic steering guidance were compared to a baseline defined as trial without haptic steering guidance. The effect of haptic steering guidance on steering performances was also evaluated in two parts: during application of haptic steering guidance and after. These scenarios were performed using a driving simulator and following conclusions were made.

1. Haptic steering guidance has effects on the neuromuscular condition of the driver depending on the steering difficulty.
2. In simple driving situations, haptic steering guidance does not have any impact on the driver.
3. In complex driving situations, haptic steering guidance relaxes drivers.

5.3.3. *Results: The influence of haptic steering guidance on driving performances*

In following paragraphs, the results that concern the variation of driving performance of the experiment presented in the section 4.4.1. are introduced.

In Figure 55, the SDLP values of trial without haptic steering guidance and trials with the different designs of haptic steering guidance are presented.

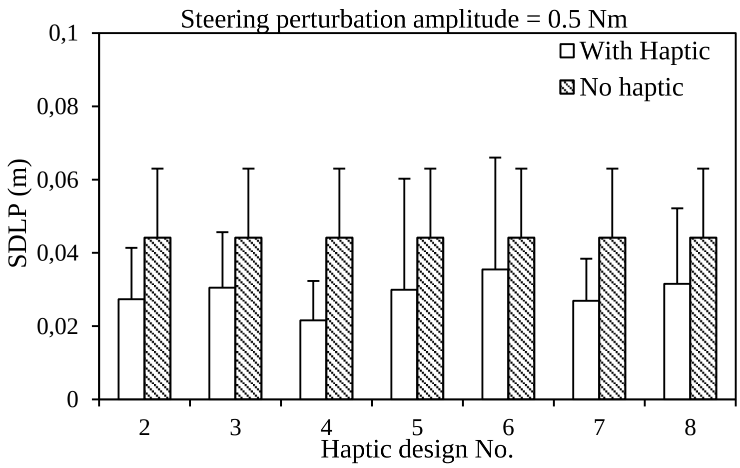


Figure 55.a. Average SDLP values at 0.5 Nm SPA.

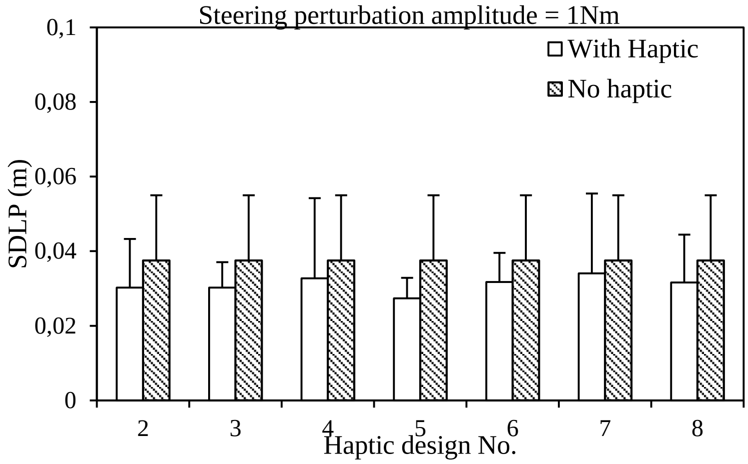


Figure 55.b. Average SDLP values at 1 Nm SPA.

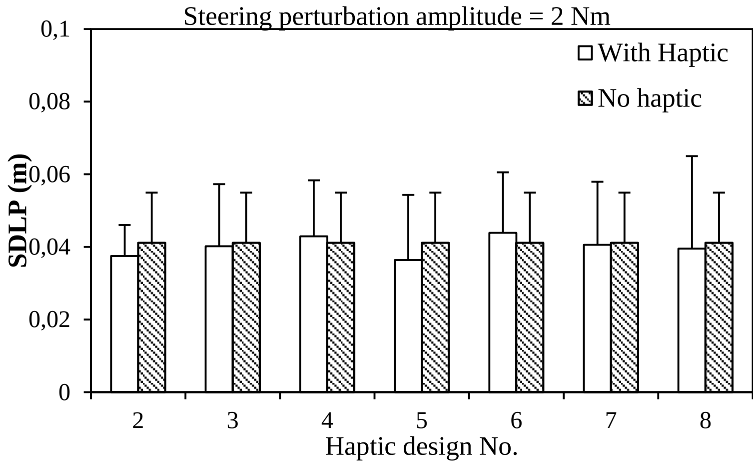


Figure 55.c. Average SDLP values at 2 Nm SPA.

Figure 55. Standard deviation of lane position for various amplitudes of steering perturbation and levels of haptic assistance.

For low steering perturbation amplitude, it can be observed that haptic steering guidance decreases the standard deviation of lane position. Whereas, for medium and high steering perturbation amplitudes, it can be noticed that haptic steering guidance does not impact the standard deviation of lane position. It expresses that haptic steering guidance is effective in reducing vehicle lateral position variability at low steering perturbation amplitude but becomes ineffective at medium and high steering perturbation amplitudes. Moreover, the time history of the lane deviation is presented in the Figure 56. In this figure, the lane deviation of the vehicle compared to the ideal trajectory of the vehicle is presented depending on the amplitude of the steering perturbation during the estimation of mechanical arm admittance.

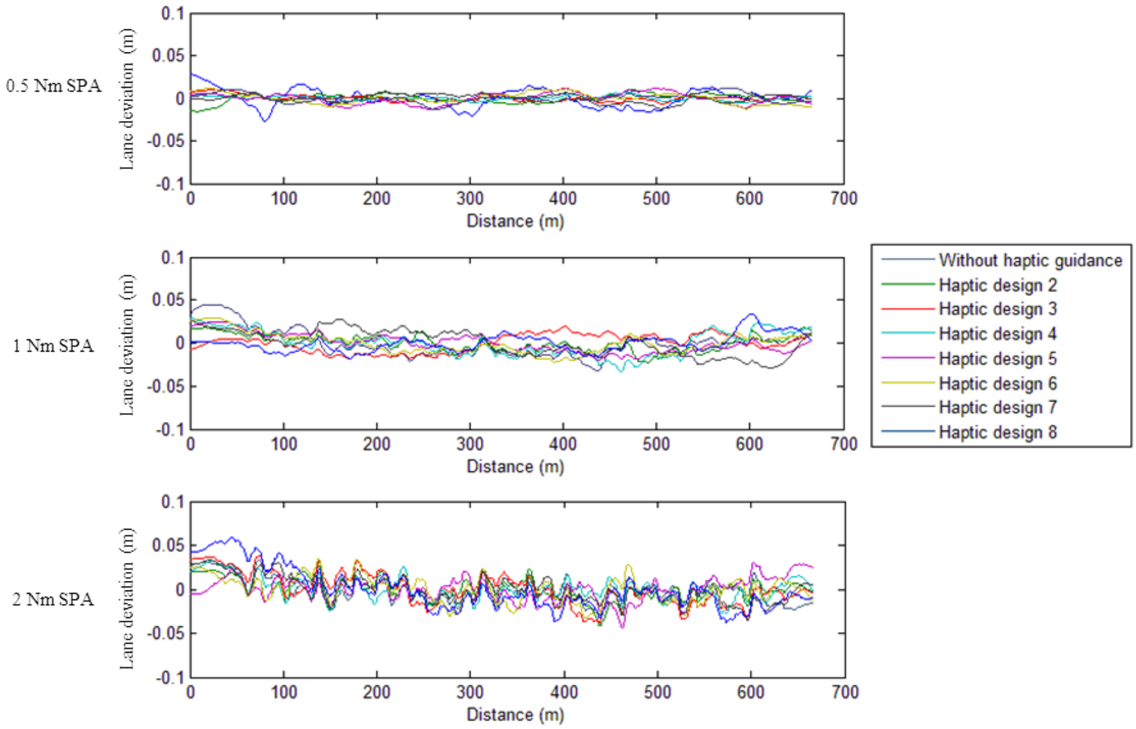


Figure 56. Time history of the standardized lane deviation for each haptic design.

It can be observed that participants express a smoother driving at low steering perturbation amplitude because of the ease of the driving task but their driving becomes tighter with the increase of steering perturbation amplitude because of the increase in the difficulty of the task. Indeed, the vehicle stability is decrease at higher amplitude of steering perturbation.

To determine whether haptic steering guidance design has a statistical impact on standard deviation of lane position, a two-way ANOVA with repeated measures was performed for the analysis of variance. Two independent variables, which are the amplitude of steering perturbations and the type of haptic design, were used for the analysis of variations of the standard deviation of lane position. It was not found any significant interaction between the steering perturbation amplitudes and the haptic design: $p = 0.084 > 0.05$, $F(14, 196) = 1.591$.

Post hoc comparisons using F-Test with Bonferroni correction that concerns effect of haptic steering guidance design at 0.5 Nm did not show a statistical significant difference in SDLP amplitudes between trials, $F(1, 13) = 2.516$, $p = 0.135$. At 1 Nm, post hoc comparisons using F-Test with Bonferroni correction did not show a statistical significant difference in SDLP amplitude between trials, $F(1, 13) = 0.051$, $p = 0.825$. At 2 Nm, post hoc comparisons using F-Test with Bonferroni correction did not show a statistical significant difference in SDLP amplitude between trials, $F(1, 13) = 0.360$, $p = 0.558$.

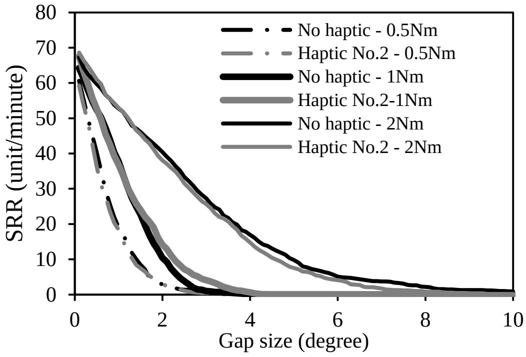
The pairwise comparison of SDLP differences is presented in Table 8. We decided to present multiple comparison results of those trials that we had an interest in, i.e., the without-haptic condition and the other seven with-haptic conditions.

For low steering perturbation amplitude, i.e. 0.5 Nm, a significant difference was found for design Nos. 2, 3, 4, 5, 7 and 8. It expresses that haptic steering guidance decreases the amplitude of lane deviation at low steering perturbation. For medium steering perturbation amplitude, i.e. 1 Nm, no significant differences were found. For high steering perturbation amplitude, i.e. 2 Nm, no significant differences were found.

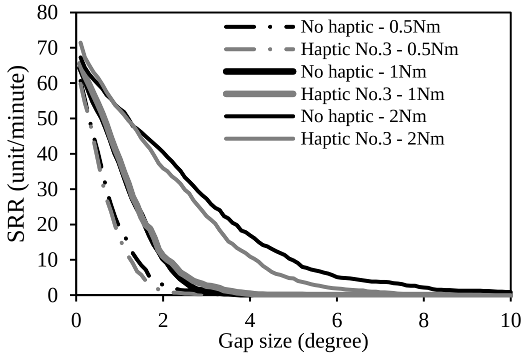
Table 8. Pairwise comparison results of SDLP for different trials without haptic steering guidance (HD 1) with trials with haptic steering guidance (HD 2 - 8).

	Low – 0.5 Nm		Medium – 1 Nm		High – 2 Nm	
	p-value	Mean diff	p-value	Mean diff	p-value	Mean diff
No haptic/2	0.042	0.017	1.000	0.01	1.000	0.002
No haptic/3	0.012	0.015	1.000	0.009	1.000	0.002
No haptic/4	0.001	0.022	1.000	0.008	1.000	-0.002
No haptic/5	0.043	0.016	1.000	0.012	1.000	0.005
No haptic/6	1.000	0.008	1.000	0.007	1.000	-0.006
No haptic/7	0.018	0.017	1.000	0.004	1.000	-0.003
No haptic/8	0.037	0.013	1.000	0.007	1.000	0.001

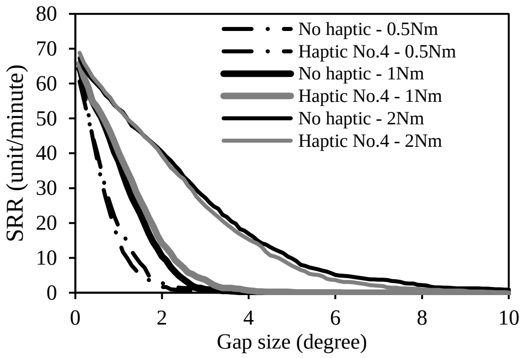
Moreover, the average steering reversal rate of participants was computed in Figure 57.



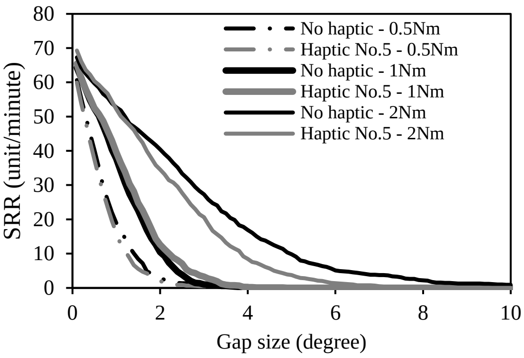
a. SRR of HD No. 2 for various SPA.



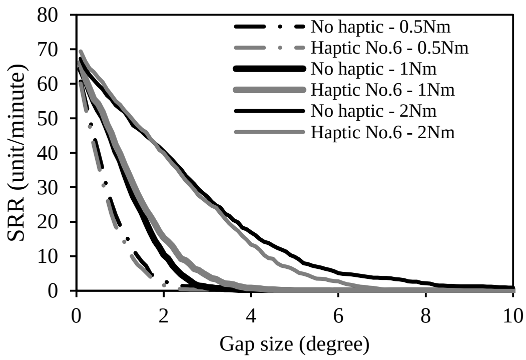
b. SRR of HD No. 3 for various SPA.



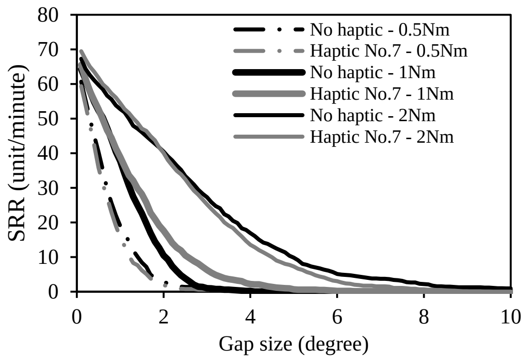
c. SRR of HD No. 4 for various SPA.



d. SRR of HD No. 5 for various SPA.

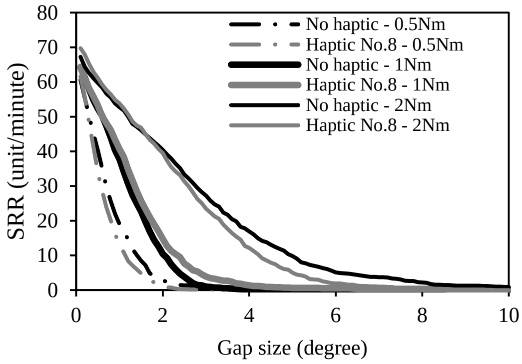


e. SRR of HD No. 6 for various SPA.



f. SRR of HD No. 7 for various SPA.

Figure 57.a. Steering Reversal Rate for the different amplitudes of steering perturbation and level of haptic assistance (a–g).



g. SRR of HD No. 8 for various SPA.

Figure 57.b. Steering Reversal Rate for the different amplitudes of steering perturbation and level of haptic assistance (a–g).

It can be observed in the Figure 57 that steering reversal rates remain similar at low steering perturbation amplitude, independently from the haptic design. Whereas, a difference tends to appear for medium and high steering perturbation amplitudes. Indeed, the steering reversal rate tends to decrease faster when haptic steering guidance design Nos. 3 and 5 are applied for medium and high steering perturbation amplitude. It expresses that haptic steering guidance helps drivers to reduce steering variability, depending on the design of haptic steering guidance.

In following paragraphs, the results that concern the variation of driving performance of the experiment presented in the section 4.4.2. are introduced.

Standard deviation of lane position has been computed during the driving task and during steering perturbation application to observe the after-effects of haptic steering guidance duration on SDLP as presented in Figures 58 and 59.

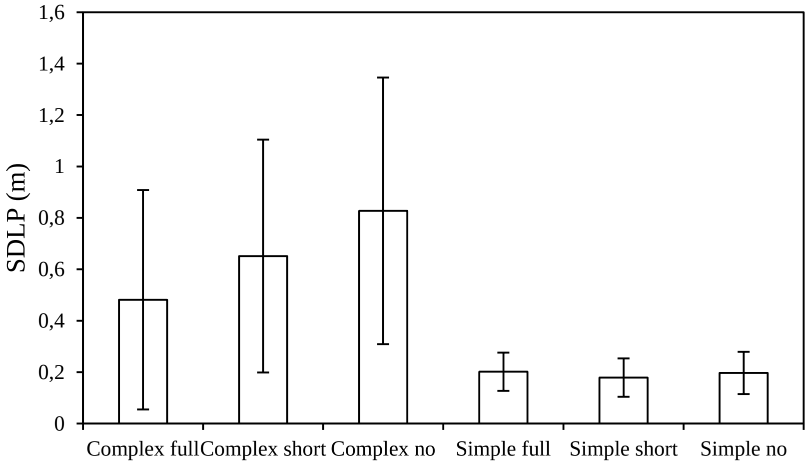


Figure 58. Mean standard deviation of lane position for simple, complex driving scenarios and different durations of haptic steering guidance during the conditioning driving task.

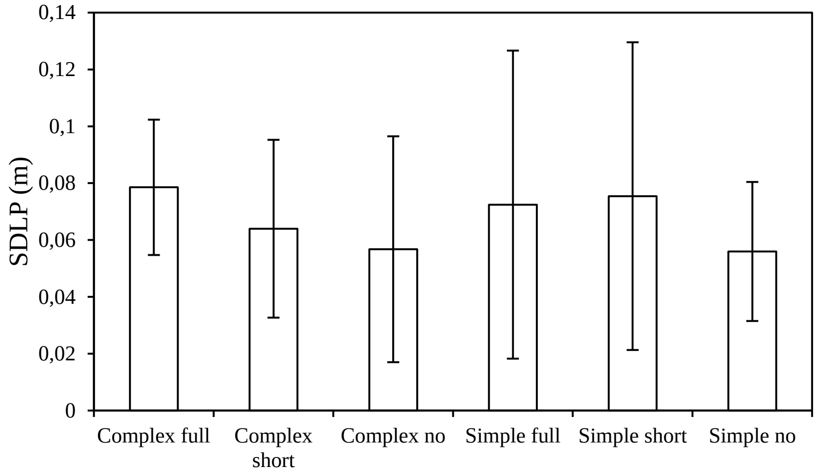


Figure 59. Mean standard deviation of lane position for simple, complex driving scenarios and different durations of haptic steering guidance during the steering perturbation application.

It can be observed in the Figure 58 that the duration of haptic steering guidance application is effective in decreasing the amplitude of the SDLP, during the conditioning task, in the complex scenario only. Indeed, it does not impact the lane keeping of the driver while performing the simple scenario as the amplitude of the SDLP in this scenario does not change. Moreover, it can be observed that the amplitudes of the SDLPs vary a lot depending on the steering difficulty.

Furthermore, it can be observed in the Figure 59 that after the conditioning task, i.e. during the estimation of the characteristics of mechanical arm admittance vie steering perturbations, the duration of haptic steering guidance application present inversion of the tendency observed the Figure 58, for the complex scenario only. Indeed, for the complex scenario, it seems that the increase in duration of haptic steering guidance application increases the amplitude of the SDLP. During the estimation of the characteristics of mechanical arm admittance of the simple scenario, the duration of haptic steering guidance application does not impact the amplitude of the SDLP.

A two-way ANOVA with repeated measures was performed to investigate the impact of haptic duration and steering difficulty on the amplitude of SDLP during the conditioning task. A significant interaction was found between steering difficulty and haptic duration; $p = 0.000$, $F(2,18) = 15.036$. The single main effect report about the amplitude of SDLP expressed that the amplitudes of SDLP is significantly decreased by the application of haptic steering guidance for the complex scenario, $p = 0.002$, $F(1,9) = 18.231$ with a mean difference of 0.346 m for the application of long term haptic steering guidance and $p = 0.000$, $F(1,9) = 50.01$ with a mean difference of 0.181 m for the application of short term haptic steering guidance.

Additionally, the SRR was computed for the conditioning task only, since it is representative of the driver performances for long term driving, as the duration of driving during the conditioning task is largely superior to the duration of driving during the estimation of mechanical arm admittance. Moreover, the SRR variations are representative for driving duration superior to one minute, and the estimation of mechanical arm admittance The results can be observed in the Figure 60.

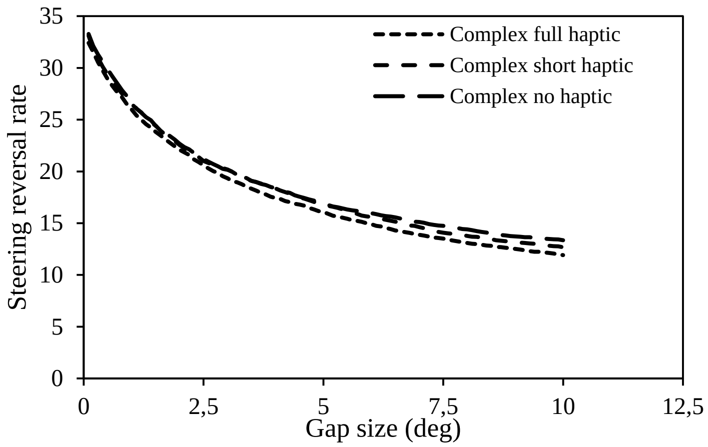


Figure 60. Average steering reversal rate for complex driving scenarios and different duration of haptic steering guidance during the conditioning task.

For the complex scenario, it can be observed that the SRR is slightly decreased by the duration of haptic steering guidance application at higher gap size. It means that participants performed large steering operations more often when the duration haptic steering guidance application was short or null. It implies that the application of haptic steering guidance is beneficial to driver when they perform difficult steering tasks, improving the steering stability. However, this difference is not significant. Thus, the application of haptic steering guidance is not significantly impacting the smoothness of the steering operations.

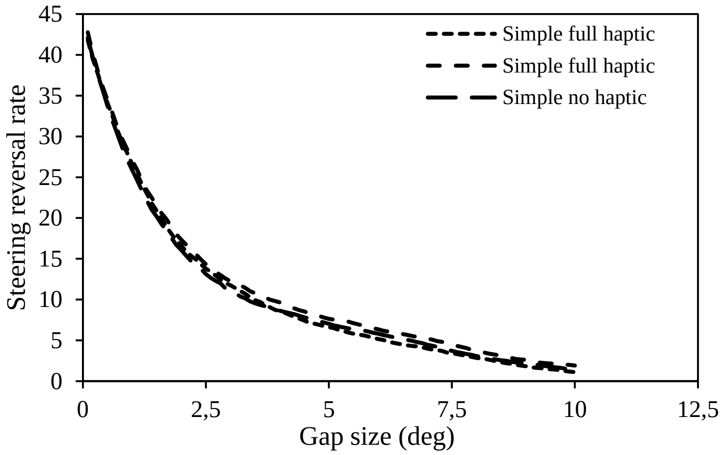


Figure 61. Average steering reversal rate for simple driving scenarios and different duration of haptic steering guidance during the conditioning task.

For the simple scenario, it cannot be observed any tendency that could indicate an influence of haptic steering guidance on steering behaviour. Furthermore, it can be observed that the steering reversal rate in the simple scenario decrease fast in comparison with the complex scenario. In the following paragraph, a discussion on the impact of application of specific haptic steering guidance design on the driving performances is presented.

Firstly, it can be observed on the Figure 55 that the amplitude of SDLP without haptic steering guidance is not affected by the amplitude of steering perturbations, as the amplitude for the three trials does not fluctuate a lot. It can be explained by influence of the steering perturbation on the vehicle lateral deviation. Indeed, the steering perturbations impact the steering wheel angle and do not affect the lateral deviation of the vehicle due to the latency of the vehicle dynamics.

As a multi sine is set to perturb the drivers, the reversal of the steering is large but its impact on the lateral deviation of the car is reduced. In our experiment, the standard deviation of lane position was significantly decreased by haptic steering guidance at low steering perturbation amplitude, independently from the type of haptic design applied to the steering wheel. However, this metric tends to show a similar level of performance when steering perturbation amplitudes were increased. Usually, larger SDLP values imply an increased likelihood of departing the lane. As a result, haptic steering guidance prevents lane departure at low steering perturbation amplitude, but become ineffective at higher steering perturbation amplitude. Being relaxed improves the smoothness of driving and standard SDLP as it can be observed in the Figure 56, which is computed with respect to the mean position of the vehicle, decreases. There is less variation in lane position because of the ease of the steering task and the assistance of haptic steering guidance. In the following paragraph, a discussion on the impact of duration of application of haptic steering guidance design and driving difficulty on the driving performances is presented.

For complex driving scenario, as haptic steering guidance provides steering assistance, participants performing complex driving tasks can improve the quality of their lane-keeping. Indeed, Marchal-Crespo et al. reviewed that drivers could learn when to initiate sharp curves or when to straighten their trajectory after exiting a curve, with the aid of haptic steering guidance [23]. The concept that guidance can improve the learning of timing is also consistent with the results of Feygin et al. [82].

It results in better steering performances that can be observed in the Figure 58, in which the SDLP is decreased when haptic steering guidance is applied to the steering wheel. The literature suggests that large SDLP values often imply high probability of lane departure [6]. The steering activity of the participants was reduced and smoother, explaining the decrease in SDLP, as reviewed by Mulder et al [12]. This result is consistent with the results of Figure 53 since it is observed that haptic steering guidance relaxes participants, featuring an increase in amplitude of mechanical arm admittance. SDLP was also computed when steering perturbations were applied. It can be observed in the Figure 59, compared to the Figure 58, that the lane keeping behavior is inversed between the conditioning task and the steering perturbation task. Indeed, lower amplitude of SDLP are observed when haptic steering guidance is activated during the conditioning task. However, this results in higher amplitudes of SDLP during the estimation of mechanical arm admittance via steering perturbations, and conversely. This suggests that haptic steering guidance has immediate after-effects on drivers that may also jeopardize driving safety, whereas scales of SDLP vary greatly during the conditioning task and during steering perturbation application. These deviations are smaller in amplitude during the application of steering perturbations due to momentary increases in muscle activation and may not be problematic for driving safety.

Steering reversal rate has been demonstrated to be a robust indicator of driver performance and steering task difficulty [66]. The results presented in the Figure 60, which presents the steering reversal rate of participants, also confirm the role of haptic steering guidance in enhancement of driving performances since assisted drivers tend to make less steering operations.

It may be acceptable to say that continuous haptic steering guidance application is a promising way to support drivers in actively producing optimal steering actions whilst driving in complex situations since it considerably enhances steering performance during the conditioning task but slightly increases trajectory deviations when steering perturbations occur, caused by the relaxation induced by haptic steering guidance application.

For simple driving scenario, the application of haptic steering guidance does not affect SDLP during the conditioning task but seems to have minor effects during the application of steering perturbations, as it can be observed in the Figure 59. Indeed, the application of haptic steering guidance seems to increase the amplitude of SDLP during the application of the steering perturbations. This is can be induced by overreliance of the driver on the haptic steering guidance system, which is consistent with the review done for complex driving situation. The driver might feel that there is a slight assistance applied to the steering wheel, so they accept it and rely on it but it does not modify their neuromuscular condition since the easiness of the steering task does not necessitate them to perform complex steering operation. Consequently, the amplitude of mechanical arm admittance is not changed in simple driving condition. Moreover, the same review can be done for the SRR on the Figure 61, which presents the evolution of the steering reversal rate with the increase of the gap size. Indeed, a difference in the steering occurrence cannot be detected, as the easiness of the task does not necessitate accurate steering wheel input. In the following paragraph a conclusion is made on the content of this section.

To investigate the influence of haptic steering guidance on the minimization of steering perturbation, diverse haptic steering guidance designs, based on the modification of feedback coefficients of the haptic model, were applied to the steering wheel. The following points can be concluded from the experimental study:

1. For a steering perturbation of 0.5-Nm amplitude, the stability of the vehicle trajectory is enhanced by haptic steering guidance, according to computation of SDLP.
2. For a steering perturbation of 1-Nm amplitude, driving operations are not affected by haptic steering guidance.
3. For a steering perturbation of 2-Nm amplitude, the steering stability is improved by haptic steering guidance that monitors the yaw rate variations.

Moreover, in order to establish its influence depending on road conditions, two scenarios were made: a complex scenario that requires frequent operations on the steering wheel and a simple scenario that does not. Furthermore, two durations of haptic steering guidance were compared to a baseline defined as trial without haptic steering guidance. The effect of haptic steering guidance on steering performances was also evaluated in two parts: during application of haptic steering guidance and after. These scenarios were performed using a driving simulator and following conclusions were made.

1. In simple driving situations, haptic steering guidance does not have any impact on the driver.
2. In complex driving situations, haptic steering guidance enhances driving performance.
3. Although long term haptic steering guidance enhances driving performance in complex driving situations, it leads to minor degradation of steering performance when haptic steering guidance is deactivated while experiencing steering perturbations.

5.3.4. *Conclusion on haptic steering guidance*

An assistance system that uses haptic steering guidance control for guiding the driver via the steering wheel is almost constantly providing steering feedbacks since the trajectory of the vehicle and the desired trajectory are often different. Indeed, the driver often prefers to adopt a steady trajectory, even if the vehicle is not in the centre of the lane. As a result, the assistance system provides steering feedbacks based on the lateral error of the vehicle in this scenario, which confirms that steering feedbacks are often provided on the steering wheel. In this situation, the driver interacts with the steering assistance system to adjust the trajectory of the vehicle, featuring a shared control of the steering wheel. The analysis of the effect of haptic steering guidance on mechanical arm admittance can be explained with different scenario. With a driver presenting a normal neuromuscular condition and a strong will to control the vehicle, it is understandable that the driver may want to overpass the control of the assistance system to control the trajectory of the vehicle as they desire. It results in an increase of the steering torque provided by the driver, an increase of the muscle stiffness and consequently a decrease in amplitude of mechanical arm admittance. With a driver presenting a normal neuromuscular condition and no special wheel to control the trajectory of the vehicle, the driver may rely on the assistance system to guide him or her through the desired trajectory. It results in a decrease of the steering torque applied by the driver in order to be guided by the assistance system, a decrease in the stiffness of the arm, and consequently an increase of the amplitude of mechanical arm admittance. With driver presenting an impaired neuromuscular condition, the question of the control of the vehicle is often avoided since the driver is not fully aware of the road environment. The application of steering feedbacks may stimulate the driver since the they do not perform any steering operation that aim to follow a decided trajectory. The addition of steering feedbacks by the assistance system act as stimulation signal that may awake the driver and consequently increase its awareness to its road environment. It results in augmentation of the steering operations performed by the driver, an increase of the steering torque applied by the driver, an increase of the stiffness of the arm of the driver, and consequently a decrease in amplitude of mechanical arm admittance. These reasons explain why haptic steering guidance has an influence of mechanical arm admittance and consequently on the condition of the driver.

Chapter 6

Discussion

6. *Discussion*

6.1. Assistance systems and neuromuscular condition of the driver

Recently, many researches, coming from various fields, have been focusing on the development of self-driving vehicles, aiming at reducing or deleting the human intervention in the driving process, which corresponds to an increase of the SAE autonomy level. This approach assumes that an automated system would not make a mistake that a human would commit (driver falling asleep, vehicle blind spot check, etc). However, this approach removes the driver from the decision loop and can leads to a diminished ability to detect system errors that lead to passiveness and drivers losing a portion of their normal awareness of the driving situation [83]. As a result, maintaining the driver in the control loop of the vehicle trajectory is considered important. Moreover, the concern of this approach is that the parametrization of a self-driving vehicle requires complex models and accurate sensors that can deal with any driving situation and ensure the driver safety.

Another approach to improve the safety on road is to increase the communication between vehicles. This approach is often referred as Vehicle-to-Vehicle communication or Vehicle-to-Infrastructure communication and aim to increase the transmission of useful information to enhance the safety for drivers. Sensors embedded in the vehicle body monitor various variables related to the driving and input them in control algorithm. The remaining uncertainty of this method comes from the unpredictable interaction between drivers, which can however be monitored using vehicle-to-vehicle communication or vehicle-to-infrastructure, and information from the environment. Usually, the vehicle-to-vehicle or vehicle-to-infrastructure is achieved by connecting the communication system of the vehicle with either the signal emitted by the infrastructure, which provides information about the environment, or other vehicles. The control algorithm processes the information and provide information to drivers or interact with the actuators of the vehicle.

In order to prevent driving accidents, prevention of impaired driving and correction of driving mistakes are commonly considered. The first approach, presented in the first paragraph, often relies on the monitoring of the trajectory and speed of the vehicle, but can also rely on the environment recognition by embedded cameras. The problem with such approach is that the cause of the driving mistakes is happening prior to its occurrence, as deprived neuromuscular condition is causing driving mistakes. If the cause of impaired driving remedied by anterior actions to the driving mistakes, harmful situation would not happen, which is the aim of this research.

Aiming at monitoring the driver condition refers to the monitoring of the neuromuscular condition of the driver [37], and being able to influence it. Within this scope, various validation conditions need to be satisfied. The first condition lies in finding a reliable method that permits to acquire the neuromuscular condition of the driver. The neuromuscular condition of the driver has been investigated in the past and models have been developed to predict its variations, depending on the steering actions performed by the drivers. These studies focused on developing mathematical models that include bio-mechanical properties of the human limbs and indicates the degree of vigilance of the driver [34][36][40]. With the interest of such characterization in the automotive industry, equivalent models that use driving variables, instead of bio-mechanical information, have been developed.

Thus, mechanical arm admittance is a metric that can be estimated using driving-related variables, or expressed in an equivalent way with bio-mechanical coefficients, which confirm its adaptability and reliability for the evaluation of the neuromuscular condition of the driver. Finally, the estimation of mechanical arm admittance allows to estimate additional features, such as data coherence that enhances the quality of the estimation of the condition of the driver.

The quality of the estimation of the neuromuscular condition of the driver, which is related to the estimation of the coherence of mechanical arm admittance in this study, is then essential to achieve this target. The advantage of using mechanical arm admittance for the estimation of the neuromuscular condition of the driver is that it permit the estimation of the coherence of the results, indicating how reliable the estimation is. Based on the value of the coherence of the estimation, the decision to influence the condition of the driver might require additional confirmation. These confirmations can be done by embedding sensors in the car body such as camera, grip sensors, or heartbeat sensors. These confirmations are needed for the detection of impaired driving.

6.2. Estimation of the condition of the driver in real-time

Consequently, mechanical arm admittance is used in this study as an estimation of the neuromuscular condition of the driver and the steering operation capacities. The interest of using mechanical arm admittance is that is can be estimated with steering perturbations for which drivers must resist at the maximum of his capacities, or using bio-mechanical properties of the limbs. The steering perturbations can be the result of road irregularities that induce side forces on the tire, which come from lateral wind on the side of the vehicle, bank angle or bump steering. They are not controllable and the driver must react properly to these perturbations in order to maintain a safe trajectory. Within the frame of the estimation of mechanical arm admittance, steering perturbation were applied to the steering wheel. Although Katzourakis et al. demonstrated the possibility to estimate mechanical arm admittance in real-time via the addition of algorithms and the application of steering perturbations with a car application [33], this approach is difficulty applicable for real-time monitoring since it would be required to apply steering perturbations constantly to investigate the NMS of the driver.

The advantage of mechanical arm admittance is that is can also be analysed via the dynamic of the arm, which includes the dynamic behaviour of the hand while gripping the steering wheel. Indeed, the equation (6) of the section 3.1.2, which was theorized by Schouten et al., demonstrates that hands biomechanical characteristics play a role in the estimation of mechanical arm admittance via the analysis of the hand stiffness and damping [36].

Consequently, mechanical arm admittance can be estimated by acquiring the pressure applied by the driver on the steering wheel. Using this approach, the application of recurrent steering perturbations is not necessary to estimate the NMS of the driver. This method was investigated in the section 4.2.1, in which the relationship between mechanical arm admittance, estimated by the method proposed by Katzourakis et al. [33], and the grip pressure applied to the steering wheel was studied.

It was found a recurrent tendency in this study that emitted that the amplitude of mechanical arm admittance is a power function of the grip pressure applied to the steering wheel. The coefficient of correlations R^2 of the tendency curves, which were determined to fit a power function, indicated a high reliability for each data set. However, this assumption is based on the upper limit of the data set, as the dispersion of data under these curves is approximative. This dispersion of data is probably caused by measurement noise when using the grip sensors. Indeed, the condition of acquisition of the grip pressure might be subjected to variations since the grip sensors were attached to gloves, which is not the best method for acquiring the grip pressure applied on the steering wheel. Moreover, the individual differences among the physical capacities of the participants might increase the spreading of data. To reduce the impact of measurement noise on the result of this investigation, a normalization method was employed, similarly to the method employed by Kong et al. to find recurrent behaviour among population with individual differences [69]. This process was not conclusive, probably because of the complex bio-mechanical mechanisms involved in the dynamics of the limbs and the impact of the measurement noise on the results. However, it might be possible to linearize this relationship to indicate the corresponding amplitude of mechanical arm admittance to the grip pressure applied to the steering wheel and evaluate more accurately the NMS of the driver. Indeed, in multivariate analysis, it is possible to linearize the relationship between variables or to normalize the residual in a regression model [84]. Moreover, it might be possible to reduce the measurement noise by using embedded grip sensors in the steering wheel, which diminishes the errors since the sensors are normally stimulated, unlike sensors attached to gloves, which the position of the sensor depends on the fitting of the glove to the hand of the participants [32]. Using this method permits to acquire the amplitude of mechanical arm admittance for real-time monitoring of the drivers.

As the amplitude of mechanical arm admittance can be acquired via the method proposed above, the corresponding NMS of the driver related to this amplitude must be known, aiming at making a decision on the need of assistance. Indeed, it was explained in the section 3.1.1 that high amplitude of mechanical arm admittance expresses a relaxed behaviour, induced by low stiffness and damping of the arm, and low amplitude of mechanical arm admittance expresses a tensed behaviour, induced by high stiffness and damping of the arm. However, the scale of amplitude of mechanical arm admittance is different for each driver as the physical capacities of each individual is different. Indeed, the steering capacity of each driver is determined by the dynamic of the joint of the upper limb and the activation of the muscles presented in the Figure 24. As a result, it is not possible to correlate the amplitude of the real-time monitoring using the same scale for each driver, which defines high and low amplitude of mechanical arm admittance. The aim of the section 4.2.2 is to evaluate the difference in scale of mechanical arm admittance for the participants, and analyse the statistical repartition of the amplitudes between the maximum and minimum value of mechanical arm admittance, which correspond to relaxed and tensed behaviour, respectively. The amplitude of the maximum steering perturbation was chosen arbitrarily to 3.5 Nm. Moreover, the amplitudes of the steering perturbations were linearly increased for the successive trials in order to investigate the corresponding variations in amplitude of mechanical arm admittance.

It was found in this experiment that the amplitude of mechanical arm admittance increases with the increase of the amplitude of steering perturbation, which is explained by the target of the driving task. Indeed, mechanical arm admittance was estimated during a PT, for which the participants should resist to steering perturbation at the maximum of their possibilities. As the amplitude of steering perturbations increases, participants cannot maintain the same level of control of the steering wheel. Consequently, the amplitude of mechanical arm admittance increases as the amplitude of the steering perturbation increase when performing a PT. This behaviour has been reviewed in similar studies that investigated the impact of variations of amplitude of steering perturbations on mechanical arm admittance [67].

Consequently, the range in amplitude of mechanical arm admittance for each individual could be acquired. This range delimitates the minimum and maximum amplitudes between which, the driver is supposed to resist correctly to steering perturbations, and can be used for real-time comparison. For example, if the real-time monitored amplitude of MAA would be higher than the upper limit of the MAA range of the participants, the assistance system could decide to provide corrective steering feedbacks in order to prevent the occurrence of lane departure. Such approach has already been proposed by Enache et al. [85], but the activation trigger in their study is based on geometrical considerations that consists in the detection of the crossing of the center lane by the front wheels of the vehicle, and is not based on the intentions of the driver and might lead to steering conflict.

It demonstrates the capacity of mechanical arm admittance to serve as an assistance metric that considers the intention of the driver.

6.3. Non-linearity in the neuromuscular condition of the driver

Moreover, it was review that a linear increase in the amplitude of steering perturbations does not induce a linear increase of the amplitude of mechanical arm admittance. Indeed, it can be reviewed in the Figure 35 that the repartition of the different amplitudes of mechanical arm admittance for each participant is irregular. This review indicates that the FRF of the driver to steering perturbation is nonlinear, which can be explained by the terms of the equations that describes mechanical arm admittance. Moreover, it was emitted by Uno et al. that the trajectory of the arm when performing a position task depends on complex nonlinear dynamics of the musculoskeletal system, which explains the nonlinear increase of the amplitude of mechanical arm admittance regarding to the linear increase of the amplitude of steering perturbations [86]. In order to investigate the statistic repartition of the amplitude of mechanical arm admittance between the minimum and maximum observed value, a descriptive statistical analysis was performed. The result of this analysis for each participant is presented in the Figure 36 and confirms that amplitudes of mechanical arm admittance are not equally distributed between the maximum and minimum value. Furthermore, it can be observed that the lower amplitudes of mechanical arm admittance are aggregated since the strip that represent the repartition between the minimum value and the first quartile is very concentrated. It indicates that the participants can present a consistent behaviour with high stiffness but are more inconsistent at lower stiffness of the arm. Moreover, Deborne et al highlighted the driver's ability to adapt different steering wheel force feedback, which substantiates the nonlinear repartition of the amplitude of mechanical arm admittance between the minimum and maximum values [87].

Therefore, the range of amplitude of mechanical arm admittance can be known beforehand and real-time monitoring of driver is made possible using embedded grip sensors that can indicate the corresponding neuromuscular condition of the driver. This direct method of acquisition of the amplitude of mechanical arm admittance must be performed with a frequency analysis by the assistance system of the grip pressure applied to embedded grip sensor in the steering wheel, looking forward providing a comprehensive acquisition of the amplitude of mechanical arm admittance depending on the frequency.

Thus, the frequency profile of the amplitude of mechanical arm admittance could be built with the assistance of the analysis of the driver torque in the frequency domain that indicates the stimulated steering frequencies and the consequent amplitude of mechanical arm admittance.

It was reviewed earlier in the amplitude of mechanical arm admittance is not consistently distributed between the minimum and maximum values for each participant. As a result, having more information via the recognition of pattern in variations of mechanical arm admittance can be the indicator of deprived state and the trigger required to provide steering assistance.

6.4. Impact of impaired driving on the neuromuscular condition of the driver

Consequently, estimating physiological influences on the neuromuscular condition of drivers by evaluating their impact on mechanical arm admittance is important to refine the acquisition of the NMS of the driver. When it comes to deprived neuromuscular condition, drowsiness or driving under the influence of alcohol are the main causes of traffic accidents. It is important to note that these issues are related to the condition of the driver, unlike speeding or reckless driving, which are related to behavioural issues. This last category of traffic accident cause is a matter of driving education, which can be prevented by providing auditory warning to the driver. Consequently, it is not investigated in this study.

Physiological changes caused by natural body cycles or being the result of external influences are impairing drivers and may harm them. They affect the neuromuscular system of the driver in such way that it is needed to investigate their mechanism and investigate their effect on mechanical arm admittance to detect their variations. This knowledge permits to recognize pattern in mechanical arm admittance and adapt the assistance of the driver. The influence of drowsiness on mechanical arm admittance has been presented in section 4.3.1.

In this experiment, the amplitude of mechanical arm admittance was compared for two stages: drowsy and alert. The method employed to induce drowsiness consisted in an accumulation of drowsiness aggravating factors such as the consumption of fast food, the reduction of the sleep time prior to the experiment, and the performance of a monotonous scenario. The monitoring of the self-evaluation of drowsiness of participants was performed using the KSS and the monitoring of the motion of the eyelid was performed to ensure the drowsy condition of the driver during the post processing of data. Mechanical arm admittance was estimated during the drowsy stage of the experiment and compared with the mechanical arm admittance of the same subjects in alert condition. This experiment aimed to highlight the influence of drowsiness on the amplitude of mechanical arm admittance and consequently on the NMS of the driver. The inducement of drowsiness was successful as the different metric that monitored the drowsiness of the participants presented values that indicated sleepiness, as it can be reviewed in the Figures 37, 38 and 39. It was reviewed that the amplitude of mechanical arm admittance is increased by drowsiness on a frequency range of 0.5 – 2.5 Hz. This increase was demonstrated to be statistically significant by the analysis of the variance, which denotes a recurrent behaviour among drivers. This recurrence is explained by the complete body exhaustion of the driver, which decreases the physical capacities [88][89]. As a result, the limb of the body becomes relaxed, which explain the decrease in the stiffness of the arm and consequently an increase in the amplitude of mechanical arm admittance. From the point of view of the assistance system, such a real-time increase in amplitude of mechanical arm admittance may trigger a warning event in which the impaired condition of the driver is considered. Indeed, the induction of drowsiness while driving is a physiological process that takes time to impact the NMS of the driver since it is often induced in monotonous conditions in which the driver is not stimulated.

Thus, the application of steering assistance may improve the condition of the driver since it stimulates the steering control of the driver who is pushed to perform additional steering perturbation. Moreover, this stimulation might mentally awake the driver. Moreover, the influence of cognitive distraction on mechanical arm admittance is studied in section 4.3.2. The aim of this experiment is to increase the mental workload of the driver using cognitive distraction and review its impact on mechanical arm admittance. Since the mental capacities of each participants is not the same, some participants were distracted by the application of a PASAT method and some were not. A PASAT test corresponds to a measure of cognitive function that assesses auditory information processing speed and flexibility, as well as calculation ability.

In order to distinguish distracted participants from alert participants, difference in amplitude of mechanical arm admittance was investigated. It was reviewed that distraction increases the amplitude of mechanical arm admittance on a frequency range of [1.4 – 2.5] Hz.

The explanation of the limited affected frequency range comes from the capacity of the NMS to provide a reflexive control of the steering wheel while facing steering perturbations. This reflexive control was reviewed to be effective until 1.1 Hz by P. van Drunen et al. [75]. Consequently, higher frequencies of steering perturbations cannot be controlled and a decrease of the arm stiffness and damping is observed, leading to an increase of the amplitude of mechanical arm admittance.

As a result, the difference in the affected frequency range by deprived condition is caused by the nature of the impairment. It was observed in the result section that the impact of impaired driving on the amplitude of mechanical arm admittance varied depending on the type of impairment, Indeed, it was reviewed that mental impairment, which was induced by an increased cognitive workload while driving, presented a partial increase in amplitude of mechanical arm admittance, located at higher frequencies, as it can be seen in Figure 45. This review indicates that mental impairment is decreasing the arm stiffness and damping of the arm on the related frequency range, leading to an adjustment of the NMS of the driver by the reflexive behaviour of the NMS at lower frequencies of steering perturbations. This difference in affected range of mechanical arm admittance is caused by the type of impairment since the physical condition of the driver is not affected by mental impairment. Thus, the driver is still able to react to steering perturbations with low dynamics, i.e. low frequency steering perturbation. That ability has the effect to show no impact of mental impairment on the amplitude of mechanical arm admittance at low frequencies. However, it was reviewed that both mental and physical impairments, which was induced by drowsiness in this dissertation, show a difference in the amplitude of mechanical arm admittance for a larger frequency range from lower to higher frequencies. Thus the driver is less able to react to steering perturbation that ranges from low dynamics to high dynamics, i.e. from low frequency to high frequency. Thus a difference in the amplitude of mechanical arm admittance can be observed from low frequencies to high frequency, denoting a decrease of the stiffness and damping of the arm on the related frequency range, which prove that drowsiness is a type of physical and mental impairment.

Furthermore, the driving performances of studies that investigate the influence of impaired conditions on mechanical arm admittance were computed via the calculation of SRR and SDLP, which can assess the smoothness of the driving and the trajectory stability, respectively. It was reviewed that impaired conditions degraded driving performances of participants. Indeed, section 4.4.3 presents the decrease in driving performances caused by both drowsiness and distraction. This is entailed by the condition of the driver that does not present the capacity to optimally control the trajectory of the vehicle. The steering operation are often shifted in time and often induce large lateral deviation of the vehicle that has been shown by many studies to endanger the safety of drivers. Moreover, it was seen in the case of distraction that a degradation in the driving performances was only visible for distracted drivers, as it can be observed in Figures 43 and 49 where subjects Nos. 3, 5, 8 and 9 were distracted by the performance of PASAT test. This indicates consistently that mechanical arm admittance is also a direct indicator of driving performances since higher amplitude of mechanical arm admittance often indicates poor driving performances.

6.5. Impact of haptic steering guidance on the neuromuscular condition of the driver

As the influence of impaired driving can be known by the monitoring of the NMS of the driver via the monitoring of mechanical arm admittance, suitable assistance can be provided to initiate the modification of the impaired neuromuscular condition of the driver. This operation can be achieved by communicating information to the driver via speakers, for example. However, the inconvenience of such information transmission is that it may disturb the driver in a way that his or her condition might also be affected negatively. Indeed, it was reviewed in previous studies that auditory and visual assistance might disturb the driver and shift their reaction time and reaction to unexpected event [41][78]. This is caused by the nature of the simulation, which is often not adapted and surprise the driver. As a result, providing continuous feedbacks to the drivers would not disturb them since they would be constantly under their influences.

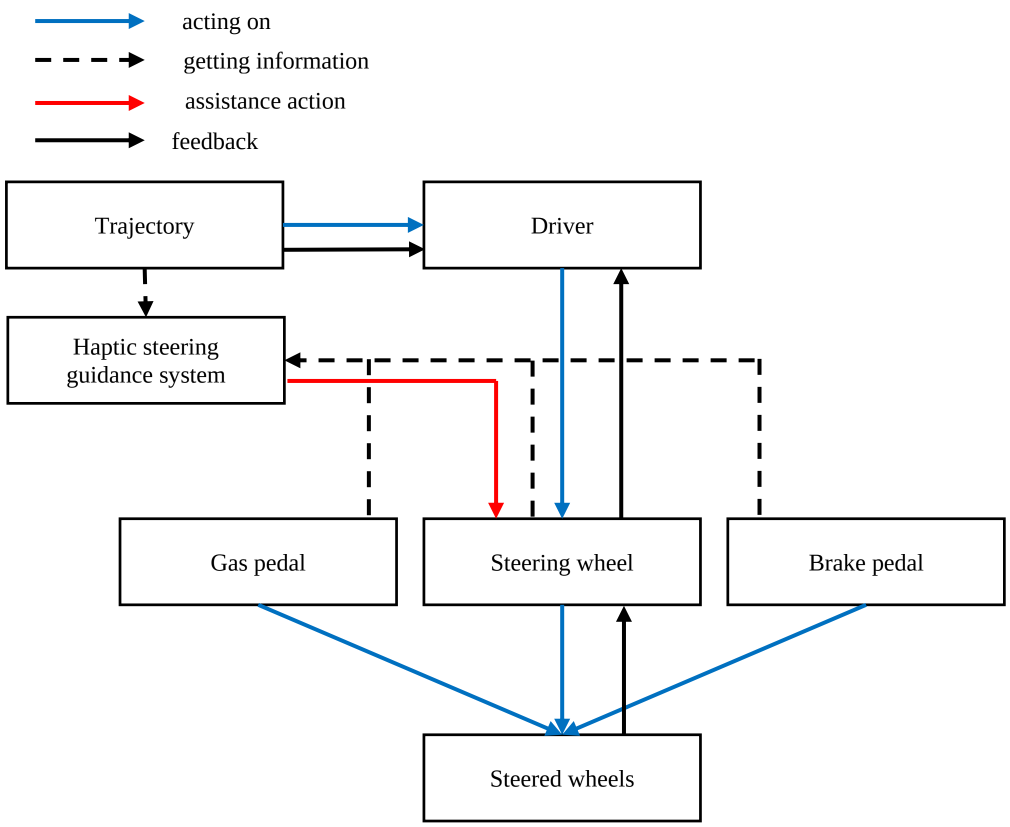


Figure 62. Interaction of the driver with the haptic steering guidance control system, the road and the actuators of the vehicle

Transmitting information via the steering wheel is adapted to fulfil this task since driver are constantly performing steering operation to control the trajectory of the vehicle. Furthermore, it does not interfere with the driver as the steering control may be possibly shared between the driver and the assistance system as it is presented in study of Abbink et al. [19]. Among steering technologies that permits to interact with the drivers, haptic steering guidance control has been demonstrated efficient to share the steering control without interference. According to this last point, haptic steering guidance control is considered in this study to influence the variation of mechanical arm admittance, and consequently influence the condition of the driver. The interactions of the driver with the assistance system are presented in the Figure 62.

In order to optimally improve the NMS of the driver, two requirements should be fulfilled. They concern the design of applied haptic steering guidance and the effect of haptic steering guidance on the driver.

The section 4.4.1 presents the impact of the application of distinctive designs of steering haptic steering guidance feedbacks on the amplitude of mechanical arm admittance. Within this scope, a special attention was paid to the feedbacks based on the yaw characteristics feedbacks of the vehicle since Güvenç proved that the rejection of yaw disturbance permits to alleviate the steering disturbance [65]. The different coefficients of the distinctive designs of haptic steering guidance control are presented in Table 6. The amplitude of mechanical arm admittance was estimated while applying the different designs of haptic steering guidance control and compared with a trial in which haptic steering guidance control was deactivated. In this experiment, it was reviewed that the amplitude of mechanical arm admittance could be decreased by the application of steering haptic steering guidance, as presented in the Figure 50 for certain type of designs of steering haptic steering guidance control. Indeed, it was reviewed significant difference in the amplitude of mechanical arm admittance before the cut-off frequency for haptic design that focus on the providing of haptic feedbacks that focus on the monitoring of the yaw rate of the vehicle and for high amplitude of steering perturbations.

This review indicates that the condition of the driver can be influenced by the application of suitable design of steering haptic steering guidance. As the condition of the driver can be acquired in real-time, as described in the paragraphs above, and can be influenced by the application of steering haptic feedbacks, the safety of the driver can be enhanced in real-time. However, this method is proven to be efficient only for non-impaired neuromuscular condition. An assumption that consists in the capacity to remedy impaired neuromuscular condition, such as drowsiness or cognitive distraction, by the application of haptic steering guidance can be done. Indeed, the application of haptic steering guidance may stimulate the driver since an 'intrusive' steering wheel input might perturb the driver and improve his or her awareness to the surrounding environment. However, this assumption is not verified in this dissertation and must be confirmed by performing an experiment that investigates the variation of the neuromuscular condition of an impaired driver who is assisted by haptic steering guidance designed according to the conclusion of this dissertation. If this assumption reveals to be true, the monitoring of the condition of the driver is made possible since impaired condition can be detected by mechanical arm admittance specific increase pattern and could be remedied by additional application of haptic steering guidance.

Moreover, the application of steering assistance might also worsen the condition of the driver as it could be reviewed in studies of Lee et al. [26]. Therefore, investigation of the condition of application of steering haptic feedbacks is necessary to understand the optimal manner to influence positively the condition of the driver.

In the section 4.4.2, the impact of long-term application of haptic steering guidance was investigated in term of real-time effect and after effect. The previously described design of steering haptic steering guidance was used to optimally influence the amplitude of mechanical arm admittance and highlight the condition of application of haptic steering guidance control. Two different durations of haptic steering guidance, plus on trial without haptic steering guidance were tested and compared for two difficulties of driving scenario. The aim of introducing two difficulties of driving scenario is also related to the condition of application of steering haptic steering guidance. As a result, a simple and a complex scenario were experienced by the participants for a short application of haptic steering guidance, a full application of haptic steering guidance and no application of haptic steering guidance during a conditioning task. Therefore, the conditions of application of steering haptic steering guidance can be investigated.

It was reviewed that the amplitude of mechanical arm admittance is increased with the increase of the application of haptic steering guidance for complex driving scenario. Moreover, the application of haptic steering guidance has no effect on the condition on the NMS of the driver when performing simple driving scenario.

For simple scenario, this is explained by the easiness off the steering task which does not require the application of steering assistance and does not consequently impact the NMS of the driver. Whereas, for complex scenario, this review is explained by the overreliance of the driver on the assistance system to deal with the control of the steering wheel and might not be optimal, since it would relax drivers. However, it was observed in section 4.5 that the driving performance were improved during complex scenario with the application of steering haptic steering guidance. This review indicates that it might be acceptable to apply short-term haptic steering guidance in complex scenario for reducing the driving load temporarily and enhancing the lane keeping of the vehicle. The distinction in the scenario complexity is required since the nature of the curve is taken into account by both the driver while performing steering operation to control the vehicle and the haptic steering guidance system to provide corrective torque to the steering wheel. As a result, the complexity of the steering operation is an important factor to be taken into account for steering assistance system. Indeed, simple steering operation does not require to operate the steering wheel, so assistance system are often ineffective. However, for complex driving scenario, the accuracy of the steering operation is important for maintaining an accurate control of the trajectory of the vehicle, and should be consequently subjected to prioritized steering assistance. This was reviewed in this dissertation by the difference in both amplitudes of mechanical arm admittance and value of SDLP.

The overreliance on the assistance system was also reviewed by Lee et al. [26] that assessed that haptic steering guidance should be used as a tool to stimulate the driver to enhance the lane keeping for maintaining a normal condition of the driver. It should not be used as a systematic assistance.

The advantage of applying haptic steering guidance is that it enhances the condition of the driver at regular interval of time, so that an impaired condition might be prevented. Indeed, the application of short term haptic guidance aim to relax the driver for a short period of time, in complex driving conditions, improving the lane keeping of the vehicle. Moreover, it enforces the driver to take over the control of the steering wheel when the haptic guidance is deactivated, improving the neuromuscular condition of the driver. However, this method might induce fatigue at long term since the driver shifts between assisted driving to non-assisted driving. As a consequence, the driver might predict the variations of assistance that might entail overreliance on the assistance system and fatigue. As a result, countering the effect of long term driving with assistance must be found.

Regarding the estimation of the coherence, it is not required for the improvement of the neuromuscular condition of the driver since the application of haptic steering guidance depends on the steering difficulty, which is related to the curvature of the trajectory of the vehicle. Indeed, the application of haptic steering guidance is proposed to be applied for short term, in complex driving situation only, at regular interval of time. By adopting this approach, the neuromuscular condition of the driver is improved continuously over the time, and is applied independently from the value of coherence.

Regarding the previous points cited in this discussion section and the intermediary sections, it is possible to realize the monitoring of the condition of the driver in real-time using haptic steering guidance interface. This task is divided in two parts: the acquisition of neuromuscular characteristics of the driver and the real-time monitoring of the neuromuscular condition of the driver.

For the acquisition of the neuromuscular characteristics of the driver, the minimum and maximum amplitude of mechanical arm admittance should be known beforehand. This task is realized by performing a PT for different amplitudes of steering perturbations. Moreover, the relationship between the grip pressure applied on the steering wheel and the amplitude of mechanical arm admittance should be known beforehand.

These two steps can be realized at the same time and should be verified regularly in order to ensure the quality of the estimation. Indeed, it was demonstrated that the condition of a person can vary depending on the environment, food consumption [90]. As a result, these variations should be acquired to reflect the need of assistance of the driver.

For realizing a real-time monitoring of the condition of the driver and influencing his or her condition, four conditions need to fulfil:

- The amplitude of mechanical arm admittance should be built based on the frequency analysis of the grip pressure applied to the steering wheel, which has a relationship with the amplitude of mechanical arm admittance.
- This amplitude should be compared with the minimum and maximum amplitude of mechanical arm admittance, which was acquired during the stage that aim to acquire of the neuromuscular characteristics of the body. A statement on the condition of the driver can be done by comparing the real-time amplitude of mechanical arm admittance to the pre-acquired amplitudes (high amplitude of mechanical arm admittance reveals lows stiffness and damping of the arm, and conversely).
- If the driving conditions are complex, the haptic steering guidance interface, that monitors the yaw rate of the vehicle may activate for short period of times to enhance the lane keeping of the vehicle, at the cost of a slight relaxation of the driver.
- If a pattern in the amplitude of mechanical arm admittance of impaired driving, which can be mental (distraction), physical, or both (drowsiness), the assistance system should take measure to ensure the safety of the driver such as the request to stop the vehicle.

6.6. Limitation of the proposed method

It was seen in the section that concerns the impact of impaired driving on mechanical arm admittance that a difference in amplitude could be detect, meaning that an impaired condition could be detected using physical channels. However, the variation in the neuromuscular condition of the driver is constituted by many different states between a normal condition and an impaired condition, highlighting that the monitoring of the neuromuscular condition of the driver consists in the analysis of intrinsic variation of the body that might not be detected clearly by the method proposed in this dissertation. As a result, the proposed method in this dissertation is quantitative instead of qualitative but can be subject to further refinement to improve the intermediate detection of the neuromuscular condition of the driver. Indeed, because of various factors that can be measurement noise of the steering grip sensors or change in the steering posture of the driver, the accurate detection of an impaired condition might be difficult to achieve. Concerning the impact of the change of the driving posture of a driver, it affects the mechanical properties of the arm while performing a steering maintenance task since the dynamic of the joints and muscles of the arm are affected by this change. As a result, though it is often recommended to maintain an optimal driving posture, it differs in real condition and this has to be taken into account for the integration of assistance system. Moreover, noise in the measurement of the grip pressure can occur since the contact of the hands of the driver with the steering wheel is not continuous. Moreover, experienced drivers tends to put hands off the steering wheel since they are confident in their driving skill that affects the outcome of this dissertation. Considering the previously cited points, the proposed method for detecting impaired condition via the estimation of the variation of the neuromuscular condition of the driver and its improvement via the application of short term haptic steering guidance should be used in addition of other traditional assistance system to ensure the quality of the estimation of the condition of the driver, aiming at improving the driving safety.

Chapter 7

Conclusion

7. *Conclusion*

The first chapter of this dissertation introduces the problematic of safety, supported by the example of Japan. Moreover, it introduces the concept of assistance system to prevent driving mistakes or provide useful information to the driver.

The second chapter expresses the importance of selecting a suitable assistance system to improve the condition of the driver. The proposed method to assist the driver is haptic steering guidance, which principle is explained.

The third chapter introduces a method to acquire the neuromuscular condition of the driver through the estimation of mechanical arm admittance, which can be expressed using different approaches. Moreover, the consideration of haptic steering guidance is discussed to enhance the neuromuscular condition of the driver.

The fourth and fifth chapters present the different experiments performed in this dissertation and their results. It starts with a description of the experimental apparatus, followed by the demonstration of a method to acquire the amplitude of mechanical arm admittance without steering perturbations. Then a method to understand the characteristics of the estimated mechanical arm admittance in real-time is provided. Following this, the detection of impaired condition using mechanical arm admittance is presented within the frame of drowsiness and distraction. Then haptic steering guidance is proposed to enhance the neuromuscular condition of the driver, via the application of a suitable design of haptic steering guidance, specific timing of application and the consideration of the driving complexity.

The sixth chapter discuss about the different interaction between the founding and proposes a method to detect impaired condition of driver and its implication with haptic steering guidance for real-time applications.

With the increase of vehicles accidents, assistance systems, which aim to interact with the drivers to correct their mistakes, have been developed. The main interaction of the driver with the vehicle trajectory is made through the steering wheel, and to a less extent, the gas pedal. The easiness of the steering wheel principle makes possible the understanding of the driver intentions in normal neuromuscular condition.

Consequently, a way to assist the driver is to increase the impact of assistance systems on the trajectory and speed control, through the steering wheel and gas pedal. The importance of the design assistance systems is to understand the condition of the driver and provide adequate assistance regarding a possible irregular condition of the driver.

Within this scope, the detection of an impaired neuromuscular condition of the driver should be performed. It can be done in an indirect way by embedding multiple sensors into the vehicle body and the command instruments of the vehicle, aiming at providing information about drivers and their interactions with the environment. A direct way to monitor drivers is to put sensors on the driver body to acquire physiological signals that indicate the condition of the driver. However, this approach isn’t realizable for commercial applications since it is annoying drivers. Indeed, these sensors give information about the driver condition, at the cost of the driving ergonomics.

As a conclusion, the previously cited indirect way to is, now, the only viable solution for monitoring drivers for commercial applications.

In the recent years, haptic steering guidance control has been proposed to influence the vehicle trajectory and speed, aiming at improving the driving quality by adding corrective actions on the steering wheel and gas pedal. Since steering haptic steering guidance is acting on the steering wheel to reduce the steering entropy, it is possible to know the intentions of the drivers by gathering the steering information and decide on the steering assistance need. By this method, drivers wouldn't be perturbed by external action on the steering wheel and their driving behaviour would be enhanced in challenging driving conditions.

A metric, called mechanical arm admittance, is used in this dissertation to assess the condition of the driver, which is related to the neuromuscular condition of the driver. As mechanical arm admittance is the image of the driver condition, its amplitude varies with the condition of the driver. An increase of the mechanical arm admittance amplitude reveals a decrease in the arm stiffness and damping, which entails an incapacity to provide adequate steering feedbacks in challenging driving situations. At the opposite, a decrease in mechanical arm admittance amplitude reveals a focused driving, which is desired for avoiding vehicle accidents.

The aim of this dissertation is to explain the underlying mechanisms of the driver condition variations and propose a method to monitor these variations using haptic steering guidance interface.

We investigated the influence of impaired conditions on mechanical arm admittance and came to the following conclusion:

1. An impaired neuromuscular condition is increasing the amplitude of mechanical arm admittance depending on the frequency.
2. The affected frequency range of amplitude of mechanical arm admittance depends on the level of impairment, as severe impairments affect larger frequency bandwidth.

As the impact of an impaired condition of the driver on mechanical arm admittance can be detected, a method is proposed to modify this impact. The proposed method to influence the condition of the driver consists in using a steering haptic steering guidance interface to stimulate drivers and we came to the following conclusion:

3. Optimal design of haptic steering guidance, aiming at decreasing the amplitude of mechanical arm admittance, focuses on the monitoring the yaw rate of the vehicle while maintaining a normal level of attention of the lateral deviation and velocity of the vehicle, and yaw angle of the vehicle.
4. The application of haptic steering guidance should be restricted in time as complex driving situations required the application of short-term steering haptic steering guidance feedbacks, and simple driving conditions do not require the application of haptic steering guidance feedbacks.

As the condition of the driver can be influenced optimally by applying haptic steering guidance control for limited period of time, its application for real time monitoring is desired. Some technical challenges are raised since the estimation of mechanical arm admittance requires the application of steering perturbations, which is not desired while driving. Moreover, real-time monitoring of the driver estimates amplitude of mechanical arm admittance of which the meaning is unknown since comparison cannot be performed. We overcame these challenges with the following conclusion:

5. It is possible to acquire the amplitude of mechanical arm admittance without steering perturbations since the grip pressure applied to the steering wheel is representative of mechanical arm admittance. Indeed, the grip pressure applied to the steering wheel is a power function of mechanical arm admittance, which its coefficients depend on the physical characteristics of each individual.
6. The understanding of the neuromuscular condition of the driver can be achieved in real-time by investigating the range of amplitude of mechanical arm admittance beforehand, while performing position tasks. Thus, it is used as boundaries between which the real-time estimation of the amplitude of mechanical arm admittance is fluctuating. Out of this range, the driver may require assistance to face challenging driving situation.

The advantage of this method is that is doesn't require annoying sensors and can be performed through the acquisition of steering wheel information in real-time. Consequently, steering assistance, which aims to assist the driver and enhance the condition of the driver, should be provided regarding the different points cited above. Moreover, the detection of an impaired condition can be done via the analysis of physical reaction of the driver, unless current driving assistance systems. It enhances the quality of the estimation of the neuromuscular condition of the driver and can provide a double validation of the estimation of the condition of the driver if coupled with another system, e.g. a camera that detects facial feature of the driver.

To sum up the content of this dissertation, a driver can be influenced positively using short term steering haptic steering feedbacks, which pay a special attention to the monitoring of the yaw rate of the vehicle, in complex driving situations. Else, the haptic steering guidance does not have effect on the condition of the driver or can even induce overreliance on the assistance system. Additionally, an impaired condition can be detected by observing increase patterns, depending on the frequency, of the amplitude of mechanical arm admittance that relate to a modification of the neuromuscular condition of the driver. Furthermore, the detection of impaired condition and the improvement of the neuromuscular condition of the driver can be made in real-time, which can fit real applications.

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List of publications

1. <u>Journal paper</u>

- Joly, A., Shimono, K., Zheng, R., Kaizuka, T., & Nakano, K. (2017). Influence of Haptic steering guidance on Arm Admittance of Drivers under Steering Perturbations. *International Journal of Intelligent Transportation Systems Research*, Vol 16(1), pp. 1 – 14.

DOI: https://doi.org/10.1007/s13177-017-0148-0

Received 31/03/2016, Accepted 22/11/2017, Revised 07/10/2017, Published 04/12/2017

- Joly, A., Zheng, R., Kaizuka, T., & Nakano, K. (2017). Effect of Drowsiness on Mechanical Arm Admittance and Driving Performances. *IET Intelligent Transport Systems*, Vol 12(3), pp. 220 – 226.

DOI: http://dx.doi.org/10.1049/iet-its.2016.0249

Received 30/09/2016, Accepted 12/11/2017, Revised 30/09/2017, Published 30/11/2017

- Joly, A., Zheng, & Nakano, K. (2018). Driver Response to Steering Perturbations: Mechanical Arm Admittance and Grip Pressure. *International Journal of Human Factors Modelling and Simulation*, Vol 6(1), pp. 65 – 80.

DOI: https://doi.org/10.1504/IJHFMS.2018.091357

Received 02/02/2017, Accepted 27/11/2017, Revised 03/11/2017, Published 19/04/2018

2. <u>Conference paper</u>

- Joly, A., Nakano, K., & Zheng, R. (2014, October). Variations in driver's mechanical admittance facing distracting tasks. In *Systems, Man and Cybernetics (SMC), 2014 IEEE International Conference on* (pp. 1952-1957). IEEE.
- Joly, A., Nakano, K., & Zheng, R. (2014, September). Relationship between Gripping Force and Mechanical Arm Admittance of a Driver under Perturbations. In *12th International Symposium on Advanced Vehicle Control* (pp. 57-62). AVEC'14.
- Joly, A., Nakano, K., & Zheng, R. (2015, October). Effect of drowsiness on mechanical arm admittance and consequences on driving performances. In *22nd ITS World Congress* (No. 2190).
- Joly, A., Zheng, R., & Nakano, K. (2015, October). A Scaling Method for Real-Time Monitoring of Mechanical Arm Admittance. In *Systems, Man, and Cybernetics (SMC), 2015 IEEE International Conference on* (pp. 1551-1556). IEEE.

Appendix

In following figures, average of mechanical arm admittance phase are showed. Average values are presented since the importance of data lies in pattern presented.

Section 4.2.2. A direct method for the estimation of mechanical arm admittance

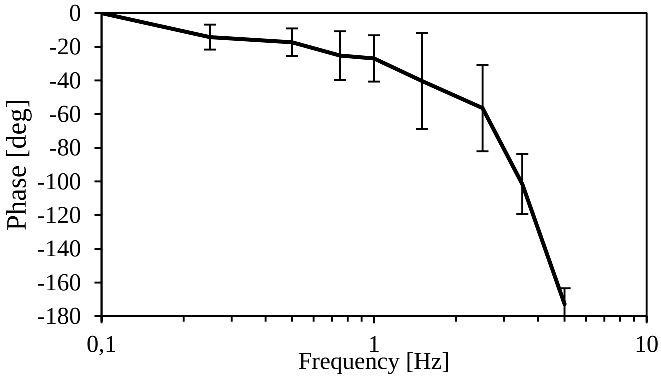


Figure 63. Average phase of mechanical arm admittance.

Moreover, the FFT of the average grip pressure of participants was plotted for each steering perturbation amplitude.

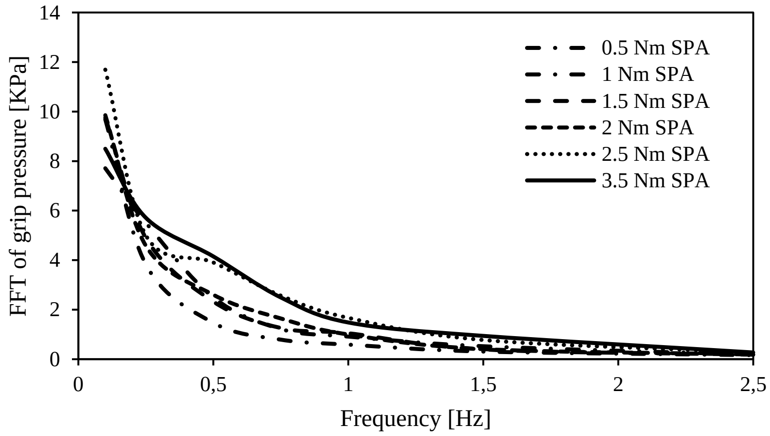
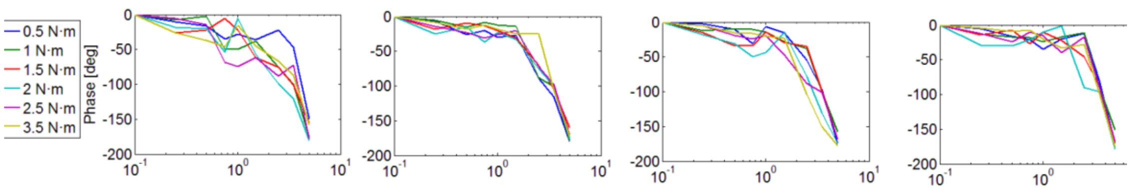


Figure 64. Fast Fourier transform of the average grip pressure of participants for each steering perturbation amplitude.

In average, the participants increase their muscle contraction, which increase the grip force, with the increase of the steering perturbation amplitude.

Section 4.3. The investigation of the amplitude scale of mechanical arm admittance



Subject 1 Subject 2 Subejct 3 Subject 4

Figure 65. Phase of mechanical arm admittance.

Section 4.3.1. The influence of drowsiness on mechanical arm admittance

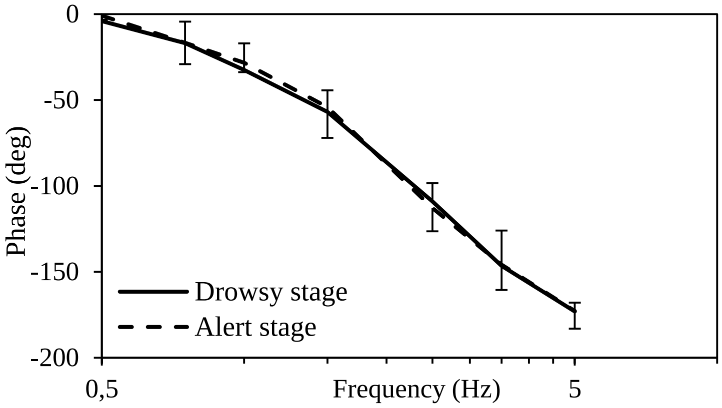


Figure 66. Averaged phase of mechanical arm admittance.

Section 4.3.2. The influence of distraction on mechanical arm admittance

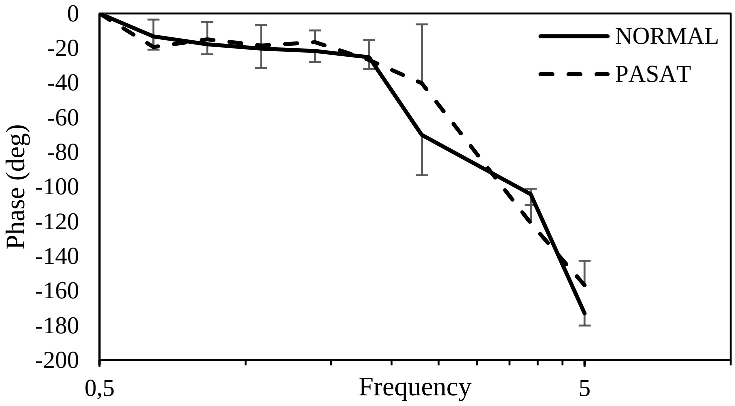
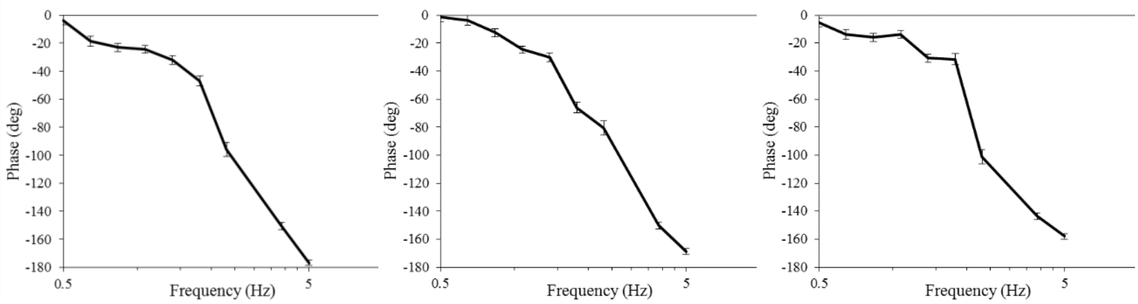


Figure 67. Averaged phase of mechanical arm admittance.

Section 4.4.1. Haptic steering guidance benefits on the condition of the driver



0.5 Nm steering perturbation amplitude | 1 Nm steering perturbation amplitude | 2 Nm steering perturbation amplitude

Figure 68. Averaged phase of mechanical arm admittance.

Moreover, the variations of mechanical arm admittance for the trials without haptic steering guidance and for the different amplitude of steering perturbation amplitude is presented in following.

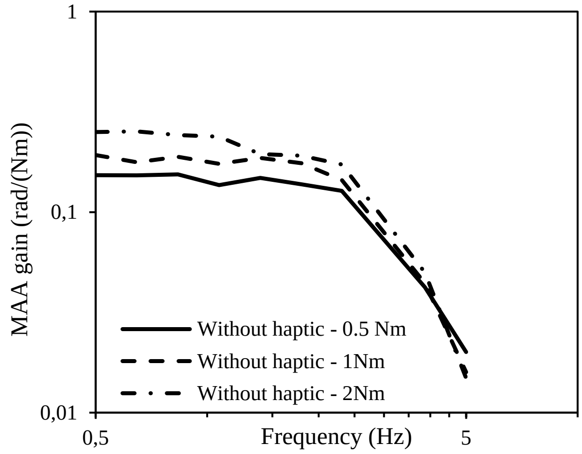


Figure 69. Variation in amplitude of mechanical arm admittance without haptic assistance for the different amplitudes of steering perturbation.

Section 4.4.2. Long term effect of haptic steering guidance application on the condition of the driver

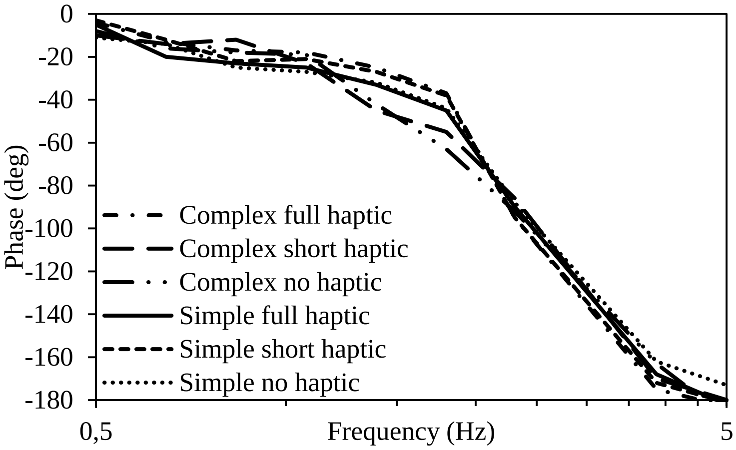


Figure 70. Phase of mechanical arm admittance.

Signal filtering for SRR computation

In order to compute the Steering Reversal Rate for estimating the variation of driving performance between different stages, the steering input from the driving simulator must be filtered to eliminate noise and enhance the quality of the estimation. As a result, the steering angle signal is filtered by a Butterworth filter. A Butterworth filter is a type of signal processing filter designed to have a frequency response as flat as possible in the passband. The effect of this treatment on the steering wheel angle can be observed in following.

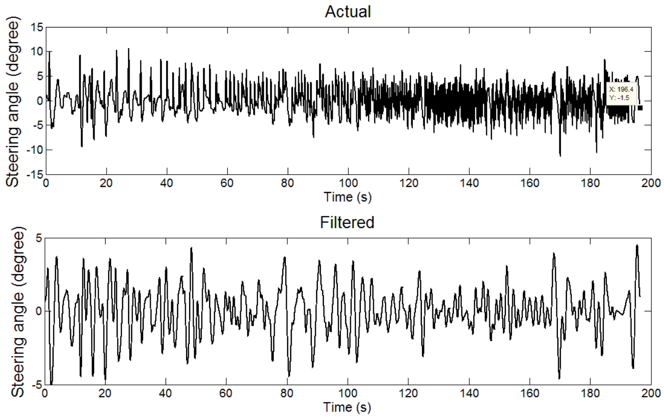


Figure 80. Filtered steering wheel angle with a Butterworth filter (upper graph is the pre-filtered signal and lower graph is the filtered signal).