Evaluation of Adapted Passenger Cars for Drivers with Physical Disabilities

Björn Peters
To all those that supported me
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Abstract
Driving can provide independent and efficient mobility. However, according to the driving license directive (91/439/EEC) are persons with locomotor impairments are only allowed drive if their disabilities can be compensated. Compensation can be realised by vehicle adaptations. The directive provides meagre guidance on how vehicles should be adapted or how to verify that the compensatory requirements are fulfilled. This is a gap in the current process for licensing drivers with physical disabilities. Furthermore, the Swedish process from driver assessment to driver licensing and adaptation approval is complex, fragmented, and suffer from lack of communication between involved authorities. The objective of this thesis was to contribute to the development of a method to evaluate vehicle adaptations for driver with physical disabilities. The focus was on the evaluation of adaptations for steering, accelerating and braking. Three driving simulator experiments and one manoeuvre test with adapted vehicles were conducted. A group of drivers with tetraplegia driving with hand controls were compared to able-bodied drivers in the first experiment. Even if the drivers with tetraplegia had a longer brake reaction time they performed comparable to the able-bodied drivers. However, they spent more effort and were more tired in order to perform as well as the able-bodied drivers. It was concluded that the adaptation was not sufficient. An Adaptive Cruise Controller (ACC) was tested in the second experiment in order to find out if it could alleviate the load on drivers using hand controls. It was found that the ACC decreased the workload on the drivers. However, ACC systems need to be adjustable and better integrated. The results from the first two experiments were used to provide some guidelines for ACC systems to be used by drivers with disabilities. The third experiment was preceded by a manoeuvre test with joystick controlled cars. The test revealed some problems, which were attributed to time lags, control interference, and lack of feedback. Four joystick designs were tested with a group of drivers with tetraplegia in the third experiment. It was concluded that time lags should be made similar to what is found in standard cars. Lateral and longitudinal control should be separated. Active feedback can improve vehicle control but should be individually adjusted. The experiments revealed that drivers with the same diagnose can be functionally very diverse. Thus, an adaptation evaluation should be made individually. Furthermore, the evaluation should include a manoeuvre test. Finally, it was concluded that the evaluation approach applied in the experiments was relevant but needs to be further developed.
**Prologue**

Mobility can almost be used as a synonym for life. Without motion there is no life. Longing for your lost mobility or yearning for the mobility you never had can be devastating for your autonomy, self-esteem and health. Technology should serve humanity and humans should not be ruled by technology. Human adaptability should not be misused to compensate for a badly engineered environment. In order to utilise what technology can offer we have to specify design requirements and guidelines, which are based on the user’s abilities and limitations. A technical solution should be evaluated with the actual user before it can be accepted. Such an evaluation shall verify that the user can carry out the intended task efficiently and with sufficient safety margins. I have tried to contribute to this objective with the work that finally led to this thesis.
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Papers
This thesis was based on the following seven papers.


VII. Peters, B. & Östlund, J. (manuscript to be submitted 2004) Joystick Controlled Driving for Drivers with Physical Disabilities - A Driving Simulator Experiment.
1 Introduction

The Swedish government’s policy for people with disabilities is based on the principles of full participation, equal living conditions, self-governing, and accessibility (Riksrevisionsverket, 1999). In line with this policy, there is a long and well-established tradition of every citizen’s equal right to mobility, independence and a good quality of life. The government has the over-all responsibility to provide accessible transports to citizens with permanent impairments such that their mobility is severely restricted. The right to financial support through a vehicle grant for purchase and adaptation of a car is one way to implement this responsibility. Access to an adapted car provides superior independent mobility compared to other modes transport for those that can drive. Swedish authorities in many ways support people with disabilities who want to drive and who fulfil the medical requirements for a driving license. However, the process for driving licensing and vehicle adaptation approval has a number of weaknesses, which are analysed and discussed in this thesis and specifically the lack of an adaptation evaluation. The department of Social Affairs is responsible for the vehicle grant and the grant is administrated through the social insurance offices. The Swedish National Road Administration (SNRA) is responsible for driving licensing and vehicle inspection directives and regulations. Fitness-to-drive assessment aiming to determine if the medical requirements for licensing are fulfilled is carried out by physicians (general practitioners and appointed medical advisors) and traffic inspectors. The Swedish Motor Vehicle Inspection Company (SMVIC), perform the mandatory vehicle inspections, both registration and annual inspection of adapted cars. SNRA has, since some years ago, also the over-all responsibility to promote accessible transports for elderly and disabled across all modes of transportation (i.e. public/private, road/rail/air/water bound transports). The driving licensing regulations do not give any detailed guidance with respect to drivers with disabilities. However, one general principle is that if a driver has a locomotor disability the vehicle should be adapted to fully compensate for the driver’s disabilities. The principle is that these drivers should be provided with adaptation that makes it possible for them to drive just as safely as drivers without disabilities. However, the directives give very little guidance on how to verify that the compensatory objectives have been achieved. Thus, there is a need to develop and validate an evaluation method for adapted cars, which can used to verify that the adaptation is sufficient. Such an evaluation could also be useful to improve the current fitness-to-drive assessment.

The work with this dissertation was guided by three objectives:

1. Describe the process for assessing and licensing drivers with physical disabilities and approval of adapted cars in Sweden.
2. Identify pros and cons in the current process and relevant regulations.
3. Develop a framework for evaluating vehicle adaptations aimed to compensate for physical disabilities.
1.1 Outline of the Thesis

This thesis was based on five published papers, one submitted paper and a manuscript to be submitted. Of the five published papers three were published in refereed journals and two published in refereed proceedings from the HFES-EC (Human Factors and Ergonomic Society – European Chapter) annual meeting. The sixth paper was submitted to Scandinavian Journal of Occupational Therapy. An abstract of the manuscript was submitted to the 3rd ICTTP (International Conference on Traffic & Transport Psychology) conference to be held in September 2004.

The thesis is divided into ten chapters with following content. The fist chapter provides a background to the problem with two explanatory examples and some examples of vehicle adaptations. The next chapter gives a short description of the target population: travellers with mobility impairments and specifically drivers of adapted cars. The succeeding chapter investigates the occurrence of incidents and accidents with adapted cars. The following chapter provides a description of how drivers with impairments are: assessed, licensed and provided with adapted cars in Sweden – the current practice. After this chapter comes a more detailed description and discussion of the process from initial assessment of fitness-to-drive to the final adaptation evaluation. Chapter seven is devoted to a presentation of driving behaviour models in view of drivers with disabilities and adapted cars. The next chapter deals with adaptation evaluation with specific focus on primary vehicle control. Chapter nine provides a summary of the experimental results presented in the accompanying papers. The final chapter contains a discussion, conclusions and a proposal for further work.
2 Background – Two Stories and some adaptation examples

Two examples of true stories and some pictures of adaptations were included with the aim to give the reader a more concrete idea of what type of problems this thesis address.

2.1 Example 1

The first example described by Oliver et al. (1997) is a story of a complicated redesign of an adapted car. The setting was as follows. The driver was a client with tetraplegia caused by a spinal cord injury (SCI) at C4 level (i.e. the neck region). The injury paralysed the client’s lower limbs and trunk and caused a reduction in sensory and motor functions in the upper limbs (arms and hands). The motor function of the driver’s left arm was superior to his right. There was a residual capacity in his biceps but his triceps were completely passive. The extent of the impairment was such that the client had to drive sitting in his electric wheelchair. Thus, the driver was provided with an electric wheelchair, a vehicle (van), and “suitable” adaptation. The wheelchair was primarily not chosen to serve as a driver’s seat but to provide the best everyday seating comfort and mobility. The vehicle was selected on the grounds that the driver should have a satisfactory eye level (not too high not too low) and that it should be accessible for a driver sitting in a wheelchair. The base of the wheelchair was sufficiently anchored to the floor of the vehicle. However, the wheelchair did not provide the necessary stability for the driver to safely control the vehicle. Furthermore, neither the primary (a four-way joystick) nor the secondary (a box with switches) controls were correctly positioned or could be operated effectively. Subsequently, the driver was not able to achieve a driver licence. The objective of the task described by Oliver (1997) was to re-design the adaptation and resolve the problems.

The difficult task with this type of adaptation is to provide the driver with a sufficiently stable seating posture and a control device that allows the driver to utilise the very best of his abilities for the primary control of the car. The re-design process included several steps. For instance both static and dynamic anthropometric assessments were carried out. The driver’s preferences were also captured and considered. Finally, the client drove the car in demanding situations as reversing, cornering and travelling over a bumpy terrain. It was found that each control interface was appropriately designed such that if the controls were positioned correctly they could be operated comfortably and effectively. The only exception was insufficient steering control by the joystick. Repositioning was not enough as driving induced fatigue, discomfort and impaired safety. This was resolved by tilting the joystick control $7^\circ$ in such a way that the driver did not have to withstand gravity forces on the “joystick hand” in curves. The next step was to solve the stability problem. The authors meant that this problem arose from lack of communication between engineers and health professionals (Oliver et al., 1997). A more suitable wheelchair should have been selected from the beginning. The way to get around this problem was to change anchorage points on the wheelchair, change the anchorage mechanism and to provide a more complex anchoring procedure, which included helpers to correctly situate the driver’s torso in the
wheelchair. Finally, the adaptation was sufficient and the client was able to obtain a driving licence.

As can be seen from this example it is not a simple task to arrive at a satisfactory solution. All the different steps in the design process contributed to the final solution. The critical conditions for a satisfactory adaptation would not have been revealed if the adaptation had not been tested with the driver on the road. The authors mean that: “The final presentation of a vehicle to the client should involve a thorough examination of the suitability of the vehicle and the interface, to the driver.” (Oliver et al., 1997).

2.2 Example 2

The second example concerns an actual accident with a joystick-controlled car driven by a driver with muscular dystrophy. The driver was experienced with his car and the adaptation e.g. a four-way joystick system. His annual driven distance was above average compared to the general driving population. The motor function (strength and range of motion) in his upper limbs was very limited and he was very dependent on sufficient support to achieve stability in his trunk and arms. The driving conditions at the time of the accident were straight road, good visibility and good friction.

A local newspaper article read as follows: “A handicapped driver drove off the E20 just south of …… at Saturday noon. The vehicle stopped in a tiled field beside the road. The car was driven with a joystick and probably something went wrong with the technical system so that the driver lost his steering control. The driver complained about back pain and was taken to the local hospital.”

A policeman reported the following: “I have examined the adapted vehicle with registration number ABC123 on behalf of the SNRA (Swedish National Road Administration). The cause of investigation was a ran-off-the-road accident. The damage included the front part of the chassis, engine, gearbox, and sheet damage. The investigation focused on the steering control system as the driver claimed that the system had made a sudden turn to the right. It turned out that both the adaptation company and the owner/driver knew of three previous similar steering incidents with the car. At one occasion the vehicle had ran into a refuge at low speed. The joystick system had been replaced. The adaptation company will replace the current steering control system and the old system will be assembled and undergo a bench test.”

A traffic inspector participated also in the investigation. He made approximately the same remarks as the policeman in his report but he gave a more detailed description of the damages. Both of them visited the accident location. They saw traces indicating that the vehicle had made a sharp turn before it left the road. However, they could not find any obstacles or signs of obstacles, which could have caused the accident. A technical investigation was conducted by the manufacturer of the joystick system but it did not reveal any clear answer to the cause of the accident. They could not find any technical malfunction in the system.
The driver did not suffer from any serious injuries. However, he did not have access to his car for one and a half-year. Now he drives to the same extent as before the accident but he does not have the same confidence in his adapted car.

The second example is different from the first in the sense that it seems like there was a malfunction in adaptation system, which caused an accident. The system was not reliable. However, it is not fully evident from the investigation that the accident was caused by a technical problem. It can also be noted that muscular dystrophy is a degenerative disease and eventually there is a risk that the driver does not have the required muscular strength or stability needed. We will probably never know the definite cause of the accident. What ever the cause of the accident was it seems as if accidents can be caused by either changes in the driver, malfunction of the adaptation – vehicle system or a mismatch between the driver and the car’s control system. A well-designed performance test could at least solve some of these problems.

Both cases show that it is a delicate task to ensure that the interface between the driver and the car is adapted to fully compensate for the driver’s impairments. In order to at least solve some of the identified problems I propose that a mandatory adaptation evaluation should be developed and tested. Such an evaluation should include a performance test of the driver - adapted vehicle system. However, it is essential that an adaptation evaluation is implemented so that serves as a support to the customer - i.e. the driver.

2.3 Some adaptation examples

The pictures on the next page were included in order to give the reader an idea of vehicle adaptations for drivers with physical disabilities. The adaptations shown are adaptations made for steering, braking and accelerating. Picture number 1 show a floor mounted mechanical brake and accelerator control. The driver holds the brake lever which is pushed forward to brake. The small lever in front with a black top is used to control the accelerator. Speed is increased by pulling the lever backwards. Picture number 2 shows a combined hydraulic brake and accelerator control. The driver rests his wrist in a forklike lever and holds a lever with his arm. The hand control in picture 3 is also a combined brake and accelerator control. This control is equipped with a special made wrist support. The driver on picture 4 uses a crutch-like stick as a temporary adaptation to control the brake in his car. Picture 5 displays a steering knob with a tri-pin grip attached to the steering wheel. The driver in picture 6 uses a hydraulic steering system with a floor mounted lever in his van. A horizontal mini steering wheel is shown in picture 7. The driver controls accelerator and brake with the small lever on the right hand side. Finally, an electro-hydraulic four-way joystick system is shown in picture 8. The driver steers by moving the lever laterally and pushes to brake and pull to accelerate. The two panels to right are used for secondary controls. These examples show just a small sample of can be found in adapted cars. The adaptations in picture 1 - 6 are used by drivers with traumatic spinal cord injuries and the last two (7 & 8) are used by drivers with muscular dystrophy.
3 Travellers and Drivers with Disabilities

This chapter gives a short description of the target population, drivers with disabilities, and an estimate of the population size. It starts with a discussion about the difference between handicap, disability, and impairment. What we usually call a handicap stems from a misfit between the human and the environment. Humans, especially able-bodied persons, can be very adaptable and thus often overcome design flaws. However, a person with a disability has less potential to adapt to a badly designed environment. The approach advocated in view of vehicle adaptation is that the environment should be fitted in accordance with user’s abilities and preferences.

3.1 Transport for People with Disabilities

The ability to freely and independently move and travel is for most people, especially non-disabled, so fundamental that it is rarely given a second thought. It is taken for granted and it should be taken for granted also for those who have some kind of disability. In general, demands and resources allocated to transporting people is steadily increasing and have been predicted to increase with 24% between 1997 and 2010 in Sweden (Braun, 2002). It can be expected that also people with disabilities want to increase their travelling e.g. drivers of adapted cars drive on average more than drivers in general (Henriksson, 2001). However, travellers with impairments are often reminded of their limitations. For example a doorsill or a kerbstone may become severe obstacle for a person using a wheelchair. Thus, it is important that the transportation system is made accessible to people with disabilities. A design for all can often provide better conditions for most users (see e.g. The European Institute for Design and Disability http://www.design-for-all.org/).

Transportation for people with disabilities is basically provided in three ways: private cars, public transportation and special transportation services, of which travelling in private cars (passenger and driver) is the most frequent mode of transport (Eriksson, 1999). The importance of having access to a car have been shown in several surveys e.g. (Henriksson & Peters, 2004; Lääperi, Seppäläinen, Luoma-Aho, & Alaranta, 1995; Nicolle, Ross, & Richardson, 1992; Peters, 2000; Örne, Hallin, & Kreuter, 1997). Even if a disability is very severe and the available resources for driving a car are very limited, it may still be possible to drive if the right adaptation is made in the vehicle. For instance some drivers with severe muscular dystrophy drive their own cars with the use of a 4-way joystick system. Among five drivers who participated in a study four fulfilled all their transport needs by driving their own car (Östlund & Peters, 1999). The fifth driver travelled as passenger in his own car (30 – 40% of the time) when he did not drive himself. For these drivers access to a car of their own was of enormous importance. Accessible transports for people with disabilities are not just a matter of equal rights. It is also of major importance for health, autonomy and well being in general. Hakamies-Blomqvist, Henriksson and Heikinen (1999) tentatively showed that mobility is important for elderly drivers’ participation, health and well being and can be financially justified with respect to public expenditure (see Figure 1).
Figure 1 “The mobility snake” as described by Hakamies – Blomqvist et al (1999).

The figure is meant to show how so called soft values like mobility, autonomy and also quality of life (not included in Figure 1) can be translated into hard financial values. The same line of causal relation can be applied to people with disabilities (Falkmer, 2001). The Swedish National Audit Office (RRV) (Riksrevisionsverket, 1999) found in an investigation of the vehicle grant that there was some evidence that mobility investments for drivers with disabilities can result in public funds savings. However, the authors stated that a more extensive cost benefit analysis is needed in order to give a definite answer.

3.2 Handicap – Disability – Impairment

In daily speech we often make no difference between *handicap*, *disability*, and *impairment*. However there are significant and conceptually important differences. World Health Organisation (WHO) (WHO, 1980) issued the International Classification of Impairments, Disabilities and Handicaps (ICIDH) which provides some useful definitions. Thus, according to WHO are the words defined as:

- *impairment* - disturbances at organ level (e.g. arm or eye),
disabilities - any restriction or inability (due to an impairment) to perform “normal” activities (e.g. walking), disturbances in function at the level of person,

handicap – any disadvantage caused by an impairment or disability which restricts the fulfilment of a normal role in society (relative to a peer member of society).

It is important to note that a handicap is not an absolute condition related to an individual, but contextual condition depending on the relationship between an individual’s resources/limitations and the design of the actual environment where the task is to be performed (e.g. driving a car). Thus, we should not speak of handicapped car drivers, but rather of car drivers with impairments or disabilities, since an appropriate adaptation of the driver’s environment will eliminate the handicap but the impairment or disability will remain.

3.3 Incidence of Disabilities

It is difficult to accurately estimate the number of persons with disabilities. Vanderheiden (1990) listed a number of complicating factors. One is that there is no clear line of demarcation between people who are disabled and those who are not. The ability/disability distribution is a continuous function rather than bimodal. Another complicating factor is data overlap. Even if we could find reliable data for groups of people with disabilities there would be a confounding problem, as some individuals have multiple disabilities. Thirdly, the disability has to be related to the task of interest in order to determine if it is of relevance, e.g. driving a car. Thus, the concern should be focused on implications for task performance rather than the medical cause to a disability, i.e. functional disabilities.

As a result there are only rough estimates of the proportion of persons with disabilities in a population. Sandhu and Wood (1990) estimated that between ten and fifteen percent of the population in most European countries had some kind of disability (e.g. mobility, hearing, vision, cognitive and speech). Elkind (1990) estimated that approximately 33 million people (about 15%) in the United States had sensory, motor or cognitive disabilities such that the impairments interfere with work performance in general. These estimates may be too conservative even if they are confounded due to the multiple disability phenomena. For instance Elkind (1990) mentioned that an additional 7 percent of the population have reading problems. This kind of disability is also relevant to consider when dealing with drivers, both from a learning perspective and the usage of ITS (Intelligent Transport Systems) applications.

In Sweden there are about 1.2 million people with some form of permanent disability, i.e. approximately 13 % of the population (Delén, 1999). The incidences of some frequent disabilities are presented in Table 1. Approximately 600,000 persons suffer from motor impairments, which frequently cause mobility problems. Even if many types of impairments can be of relevance to an individual’s ability to drive a car, it is mostly among those with motor impairments we find drivers of adapted cars. Many of
these (75%) are over 65 years old. More than 200,000 persons need assistance in order to move and 90,000 are wheelchair users (Delén, 1999). Many wheelchair users are institutionalised and, thus, cannot be considered as potential drivers. Some with less severe motor impairments, often non-wheelchair users, can drive without any adaptation in the car and some have so complex and extensive impairments that not even the most advanced adaptation can help them to drive. In between there is a group of potential drivers who can drive an adapted car, e.g. people with spinal cord injuries. It is with this category of drivers that most of the current experience in adapting cars was gained.

Table 1 Summary of disability groups (estimates) in Sweden (from Delén, 1999. The total number of persons with disabilities exceeds 1.2 millions mentioned. This is probably due to double counting of individuals with multiple disabilities.

<table>
<thead>
<tr>
<th>Disability</th>
<th>Persons (thousands)</th>
<th>Percentage of Population</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensory</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Visual impairment</td>
<td>175</td>
<td>1.9</td>
</tr>
<tr>
<td>(of which) blind</td>
<td>13</td>
<td>0.1</td>
</tr>
<tr>
<td>Hearing impairment</td>
<td>780</td>
<td>8.6</td>
</tr>
<tr>
<td>(of which) depending on hearing aid</td>
<td>300</td>
<td>3.3</td>
</tr>
<tr>
<td>(of which) deaf</td>
<td>14</td>
<td>0.2</td>
</tr>
<tr>
<td>Motor</td>
<td>600</td>
<td>6.6</td>
</tr>
<tr>
<td>(of which) depending mobility aid</td>
<td>200</td>
<td>2.2</td>
</tr>
<tr>
<td>(of which) wheelchair users</td>
<td>90</td>
<td>1.0</td>
</tr>
<tr>
<td>Cognitive (mental retardation)</td>
<td>40</td>
<td>0.4</td>
</tr>
<tr>
<td>(of which) sever mental retardation</td>
<td>16</td>
<td>0.2</td>
</tr>
<tr>
<td>Total</td>
<td>1595</td>
<td>17.7</td>
</tr>
</tbody>
</table>

3.4 Drivers with Disabilities

The actual target population for this dissertation was drivers and potential drivers with physical disabilities. As mentioned above, there are several complicating factors affecting the chances to get accurate estimates of the population size. Some disabilities affect the ability to drive according to the medical licensing requirements while others do not. For instance a deaf driver certainly has a disability that does influence the driving ability. However it does not constitute a formal obstacle for getting a driving licence. On the other hand there are licensed drivers with long experience who have visual impairment that they are not aware of, i.e. the impairment was not detected when they were licensed. When the impairment is detected at a medical assessment later (e.g. medical assessment is mandatory in order to keep a license for driving heavy vehicles after the age of 45) the license is withdrawn. This is done disregarding the possibility that the driver might have been driving successfully for more than 25 years. This situation has led to some controversy in both Sweden and England. Furthermore, there are disabilities like reading disabilities that are regarded as irrelevant once the license test has been passed. However, this dissertation is concerned with drivers with...
physical disabilities such that they cannot drive a standard production car unless it is
adapted. Thus, compensatory adaptation is what determines this target group.

Consequently it becomes relevant to define what an adaptation is. Can an automatic
gearbox be considered as an adaptation? Strictly, it is not an adaptation in the sense
that the car is not modified, automatic gearbox is an option when buying a standard
car. However, it may well be a specific requirement due to the driver’s disability. In
that sense it is an adaptation. What is a comfortable option for some drivers may be a
necessity for other drivers. In a limited sense an adaptation is thus when a standard
production car has to be changed to fit the driver. A standard production car is a car that
can be “delivered off-the-shelf” or ordered as a variety within the manufacturers
production program. Yet another way to define adaptation can be based on the whole
vehicle type-approval. Type approval applies only to standard production cars. If any
changes are made to the car the type approval does not apply any more. The type-
approval is described in detail in Commission Directive 98/14/EC. Finally, depending
on the reversibility of the adaptation four different levels of adaptations could be
distinguished (modification, conversion, adaptation and reconstruction) from easily
reversible to very difficult to reverse or even irreversible (Fulland & Peters, 1999b).

Swedish legislation requires that all adapted cars are inspected and approved by the
vehicle inspection SMVIC (The Swedish Motor Vehicle Inspection Company). This is
called registration inspection and is mandatory for all kinds of changes made to motor
vehicles - not just adapted cars. When approved, the adapted car will be registered as
adapted in the vehicle register. However, there are some adaptations (i.e. left
accelerator, steering wheel spinners) which are excepted from the mandatory
registration inspection. It is the responsibility of the car owner that the car pass a
registration inspection before it is used. Today some car manufacturers, e.g. Fiat and
Volvo have established co-operations with adaptation companies and can deliver cars
with optional adaptations as hand controlled accelerator and brake (Fulland & Peters,
1999a). Whether these cars will be registered as adapted in the national vehicle register
is not fully clear. In principle they should be identified as adapted but as the car
manufacturer approve of the adaptation equipment, the car should fall under the whole
vehicle type-approval. If all adapted cars were registered as such then it would be
rather easy to get a fairly accurate estimate of drivers with adapted cars.

So how can we estimate the number of drivers with disabilities and specifically those
who driver adapted vehicles? It seems like we have to accept fairly crude estimates of
how many drivers with disabilities there are. Haslegrave (1986) estimated that 0.5
percent of all drivers in Europe were drivers with disabilities and that 0.2 percent were
dependent on having the car adapted. In 1997, the National Highway Traffic Safety
Administration (NHTSA) estimate the number of adapted cars in the United States,
which was then reported in a NHTSA research note (NHTSA, 1997). Based on tow-away crash data from 1995 – 1996 they estimated that approximately 0.2 percent of all registered vehicles in the United States or 383,000 vehicles had some kind of adaptive equipment. They also noted that since the Americans with Disability Act (ADA) was passed in 1990 the number of adapted cars has increased. Applying these percentages to Swedish conditions implies that there should be about 26,000 drivers with physical disabilities and just over 10,500 drivers with adapted cars. This is probably an underestimation. Based on the number of vehicle grants approved by the Social Insurance authorities there should be about 15,000 or more Swedish drivers with adapted cars (Peters, 1998). But even this number can be too low, since there are several drivers who have financed their car adaptations by sources other than public vehicle grant e.g. driver that are over 65 year of age.

What information can be obtained from existing relevant databases, such as the vehicle register and the driving licence register? It turns out that even with access to these databases it is very difficult to correctly identify drivers of adapted cars or the adapted cars themselves (Peters, 1998). The vehicle register holds information about adapted vehicles but the reliability is somewhat doubtful. In May 1999 there were 5,384 cars identified as adapted. This is obviously much less than the 15,000 mentioned above. This difference could partly be explained as a result of the previously described exceptions from the mandatory registration inspection but far from all. A more plausible explanation is that there is a leakage in the current routines for registration inspection of adapted cars. Some adapted cars, specifically those with simple adaptations have never been inspected, approved and registered. The mandatory annual inspection does not detect and correct this failure. In addition, some vehicles, once registered as adapted, could remain as such even if the adaptation has been removed. If the adaptation equipment is removed from a vehicle it should be re-inspected, approved and registered as non-adapted. In a recent investigation based on information from the vehicle register it was found that approximately 20 percent of the vehicles registered as adapted in fact were not adapted (Henriksson, 2001).

What information can be obtained from the Swedish driving licence register? Driving licences for drivers with disabilities that were issued before 1996 had a note telling that certain conditions apply for the license. In 1996, a coding system was introduced to specify which conditions applied to the license i.e. medical reason and adaptation requirements (Vägverket, 1996a, 1998a, 1999). Only a few codes are used to specify medical conditions. Most codes are used to describe the adaptation required. Eventually, this coding system will make it possible to identify all drivers with conditioned licenses and the cause. In 1998 there were 17,736 driving licences with conditions (excluding glasses) (Kjällström, 1999). However, it was not possible to verify if all of these were drivers of adapted cars and if all drivers of adapted cars were included.

In summary, it seems like there should be somewhere between 15,000 and 20,000 Swedish drivers with disabilities such that they require cars that are adapted. Based on this estimation between 0.3 - 0.4 percent of the driving population in Sweden drive
adapted cars. This could be compared to 0.2% estimated for UK and the US (Haslegrave, 1986; NHTSA, 1997). There is, however, much uncertainty in these estimations. It may seem surprising that there should be proportionally more drivers with disabilities in Sweden than other countries. On the other hand this could actually be true due to better financial conditions and more generous criteria used to assess fitness-to-drive in Sweden compared to other countries e.g. more advanced adaptations are used and approved in Scandinavian countries.
4 Traffic Safety and Adapted Cars

This chapter deals with traffic safety aspects of adapted cars. A higher accident involvement for drivers of adapted cars could be an argument for introducing a mandatory adaptation evaluation. Thus, surveys and accident data analysis are presented and discussed. However, some aspects of safety and risk are discussed initially. The concept of sufficient safety is introduced. Evans (1991) made a distinction between accident and crash and advocated the use of crash. He meant that accident conveyed a deficient sense of fate and devoid of predictability. However, accident and crash are use synonymously in this thesis.

4.1 Traffic Safety and Risk

Driving is associated with a risk of being injured or killed. Annually, approx. 500 people are killed in road accidents in Sweden and 40,000 in Europe. Driving concerns a majority of the population. There are 5.3 million driving license holders (total population 9 million) in Sweden (SNRA official statistics).

Safety is a precondition for sustained mobility. However, total safety would imply no mobility at all. In other words there is always a risk in being mobile (Rumar, 1988). However, mobility should not be achieved at the cost of low safety. Thus, the goal should be to provide mobility with at least sufficient safety. What sufficient safety means in practical term will be explained in the following.

Safety can be divided into statistical safety and experienced safety. Rumar expressed this as collective risk and individual safety (Rumar, 1988). There is a difference between what the statistics show and what the individual perceives. Thus, it is possible to make a distinction between subjective (experienced) and objective (statistical) safety. An adaptation evaluation should strive to maximise the objective safety but also consider the subjective safety in order to achieve the mobility objectives. Subjective safety will also have a great influence on the driver’s trust. Trust can be divided into the driver’s trust in his or her own ability to handle the car and the driver’s trust in the vehicle and the adaptation (Muir & Moray, 1994; Östlund & Peters, 1999). Both these aspects of trust can be influenced by the drivers experienced safety. Thus, it is important that the driver is well trained to drive with the adaptation and knows the function and limitations of the adaptation. Objective safety will not alone convince a driver with a disability caused by e.g. a traffic accident that it will be safe to drive an adapted car. Thus, sufficient safety implies that both subjective and objective safety should be considered in order to determine if an adaptation serves its purposes. Trust should be a concern in an adaptation evaluation (see section 6.9).

Safety can also be divided into preventive and protective safety (also called active and passive safety). Preventive safety is related to the driver’s possibilities to avoid a crash while protective safety concerns the risk of being injured in case of a crash. The preventive safety level depends on the driver’s skills, behaviour and performance resources but also on the design of the vehicle and the interface between the driver and
the vehicle i.e. the adaptation. Protective safety largely depends on the design of the vehicle including the adaptation (e.g. impact injury), protections systems (e.g. airbags, safety belts), road and traffic environment and the body’s ability to withstand crash forces. Both preventive and protective safety is critical for drivers of adapted cars. The over-all ambition should be to guarantee the same level of preventive and protective safety as for other drivers (Koppa, 1990). However, it may turn out that this intention cannot always be fulfilled. An airbag system or a safety belt could cause substantial injuries to a driver with disabilities in case of a crash because the driver cannot withstand the forces from the protective safety system. Sometimes protective safety systems have to be deactivated or removed because it is incompatible with the adaptation. In these cases a trade-off between safety and mobility has to be made. This was a problem that was highlighted early in a report by Olofsson (1972) who at that time was the headmaster of a driving school for drivers with disabilities run by AMU in Hedemora. A higher risk of being injured can perhaps be accepted if the driver is aware of the risk and there are no other technical solutions available. The objective should always be to provide as good protective safety as possible but a degraded protective safety can be the price of being mobile. However, compromising with preventive safety cannot be accepted, as a low preventive safety would increase the risk for other road users. Thus, sufficient safety could occasionally mean a degraded protective safety but never a degraded preventive safety.

Yet another aspect of safety concerns the load on the driver while driving. If the driver has to spend too much effort (mental and physical) to be able to drive this will increase the risk and especially the preventive safety can be severely degraded. The adaptation should for instance ensure comfortable driving. If the adaptation is not sufficient there is a risk of over-loading the driver which can cause spastic cramps and physical fatigue and thus affect the preventive safety. This will be further discussed in chapter 6 and 8.

Finally, it is reasonable that the guiding principle in directives, regulations, and recommendations for adapted cars is to use the same safety criteria for as for cars used by drivers without disabilities. This means that safety requirements should be neither higher nor lower compared to what apply to drivers without disabilities. However, there can be some ethical dilemmas associated with the trade-off between safety and independent mobility (Cook & Semmler, 1991).

4.2 Accident Involvement

Much of the research and development in the area of vehicle adaptations has focused on mobility aspects (Koppa, 1990). This is not to say that safety has been neglected, but rather that it has not been as highly prioritised as the mobility objectives. Sometimes there seems to be a willingness to accept a higher risk as a price for improved mobility. Koppa (1980), for instance, claimed that protective safety should be more considered in adapted cars. Sagberg et al. (2003) pointed at a number of potential problems with adapted cars that could affect traffic safety. Curry and Southall (2002) identified problems with manual
braking systems which affected the drivers’ braking ability. Do these potential problems with adapted cars show up in the accident statistics?

Very little is actually known about accidents and incidents in which drivers with disabilities and adapted cars were involved. To some extent, this lack of knowledge is due to the problems of identifying the target group and their cars. This unsatisfactory situation was highlighted already 25 years ago in a report from TFD (Transportforskningsdelegationen, 1978). Very little has been done to overcome this situation and the problems remain (Fulland & Peters, 1999b; Henriksson & Peters, 2004; Sagberg et al., 2003). According to the TFD report several of the surveys existing at that time suffered from methodological deficiencies. However, the predominant assumption seems to be that drivers with disabilities do not differ from drivers in general with respect to traffic accident involvement and types of accidents (Peters, 1998). According to a research note (NHTSA, 1997), based on a statistical analysis of tow-away crashes where at least one adapted car was involved, it is reasonable to assume that vehicles with adaptive equipment are neither over- nor under-represented in crashes. This was also the conclusion drawn by Sagberg et al. (2003). There are very few surveys addressing the accident involvement of drivers with disabilities but there are some worth mentioning.

Lääperi et al. (1995) used records from a Finnish insurance rehabilitation agency to send a questionnaire to 149 clients (79% men and 21% females). The analysis showed that a group of 105 drivers (approx. 70 percent response rate) with physical disabilities (of which 60% were drivers with SCI) driving adapted cars had a slightly higher accident rate (7.6%) compared to other drivers (7.0%). However, the authors concluded that drivers with disabilities do not constitute a risk factor different from other drivers. This conclusion was strengthened when exposure was considered. The same study showed that drivers with disabilities had a somewhat lower accident rate, 3.8 accidents per 10^6 kilometres compared to 4.1 accidents per 10^6 kilometres for the average driving population. It can be assumed that the differences above were not significant even if the authors do not explicitly mention this in their report. The accidents included were minor accidents. Thus, lethal injuries were not included. The same investigation revealed that the youngest drivers had considerably more accidents compared to other age groups (Lääperi et al., 1995). The same accident pattern was found in a study involving over 1500 former learner drivers with physical disabilities at the Banstead Mobility Centre (Simms & O'Toole, 1993) in the UK. Furthermore, it seems also to be valid for the conditions in the US (Long, 1974). Thus, it is likely that drivers with disabilities have the same age related accident pattern as drivers in general.

Sagberg et al. (2003) analysed crash data for a sample of 194 adapted cars from the files of the two large insurance companies in Norway. When considering the registered annual driven distance as a measure of exposure it was found that drivers of adapted cars were not involved in more accidents 10.3 crashes per 10^6 kilometres compared to drivers in general 10.1 crashes per 10^6 kilometres. However, they did not want to exclude the possibility that drivers of adapted cars run a higher risk. They meant
drivers with adapted cars could be compensating for a difficult task by driving more carefully and that this might explain the findings. Finally, they did not want to exclude the possibility that there could be considerable differences in risk between different types of adaptations.

A Swedish survey was conducted among a random sample of 1,325 owners of cars registered as adapted (Henriksson & Peters, 2004), see also Paper V. The sample consisted of 25% of all cars registered as adapted in Sweden. The main objective of this study was to investigate accident involvement for drivers of adapted cars and compare to drivers in general. A second objective was to collect background data about drivers with disabilities e.g. type of diagnosis, functional disability and also data about the different adaptations. Thus, the primary target group was drivers of adapted cars. The only feasible way to reach these drivers was by use of the Swedish national vehicle register. Since 20 percent of the vehicles were incorrectly registered as adapted the net sample was 1038 cars that were driven by driver who had some kind of disability. The results were based on 793 completed questionnaires, which meant a response rate of 76 percent. It should be noted that all adapted cars in Sweden are not registered as such as was described in section 3.4. The questionnaire, which was sent by post, was rather extensive, 12 pages with 31 questions, including questions about e.g. disability, vehicle adaptation, driving habits, and accident involvement. This made it a quite unique investigation with focus on drivers with disabilities. The respondents were asked about their involvement in traffic accidents for the preceding 3.5 years (1996 – Mid 1999). They were also asked whether or not the accident was reported to the police. Eighty-four drivers (approx. 11 percent) had been involved in almost 100 accidents of which 31 were reported to the police during the reporting period. In all, only 13 accidents lead to personal injuries. Data about fatalities could not be extracted from the questionnaires and therefore an estimation was done based on the in-depth studies; one driver with disabilities was killed during the 3.5 years long reporting period. Driving habit data from the questionnaire were used as a measure of exposure. These data were compared to official statistics of police reported accidents (Vägverket, 2002) and travel data (Edwards, Nilsson, Thulin, & Vorwerk, 2000) in order to find out if drivers of adapted cars are subjected to a higher risk in traffic. The result of the analysis is shown in Figure 2.
The risks did not differ significantly between drivers of adapted cars and the general driving population. A 95 % confidence interval for the relative risk of accident involvement, 0.85/0.98, could be calculated to 0.61 - 1.23, hence it can not be rejected that the quota could be equal to 1.

Considering the three cited studies we can see that the estimated risk varies between approx. 1 to 10 accidents per $10^6$ kilometres driven (Henriksson & Peters, 2004; Lääperi et al., 1995; Sagberg et al., 2003). This unexpected rather great variation between comparable countries highlights one of the methodological problems. In many studies accidents or crashes are not sufficiently defined in order to be compared to other studies. All three studies included possibly both minor and severe accidents. However, only police reported accidents including fatal accidents were considered in the Swedish study. Whether or not the accidents included in Finnish and Norwegian studies were police reported is not clear. The higher accident rates make it likely that they included minor (material) accidents that were not reported to the police. However, they did not for sure include fatal accidents. Despite this, more important was that the comparisons made within the three studies were done correctly. It seems like all three studies point in the same direction and currently there is nothing indicating that drivers of adapted cars should be at a higher risk compared to drivers in general. Objective safety at least seems to be satisfactory.

However, there are several reasons why we cannot be definitely sure. For instance there is a need to further investigate causes and consequences of accidents involving drivers with disabilities and to study various groups of drivers with disabilities and types of adaptations (Fulland & Peters, 1999b; Sagberg et al., 2003). There is a need for in-depth studies of fatal accidents. Finally, there is a group of drivers or ex-drivers who gave up driving because they felt uncertain due to e.g. insufficient adaptation or lack of trust. These drivers are probably underrepresented in the reported surveys.
Subjective safety does not always seem to be satisfactory (Henriksson & Peters, 2004; Sagberg et al., 2003)
5 Licensing Drivers with Disabilities and Approval of Adapted Cars in Sweden

This chapter describes the current routines for assessing and licensing drivers with physical disabilities in Sweden. A number of weaknesses are identified. A more extensive discussion on this subject can be found in a separate report (Fulland & Peters, 1999b). The report compares the situation in Sweden to other Scandinavian countries and to other countries across the world.

5.1 Background

In Sweden, the government and the parliament have declared that resources should be allocated to make the transport system accessible for all including people with disabilities. The Swedish National Road Administration (SNRA) has been appointed the responsibility to ensure that the national transport system is accessible across all modes of transportation. In line with this objective the parliament has decided that citizens with disabilities who want and who are fit to drive a car should be financially supported to cover the extra costs, which their disability may cause. This decision was realised by the implementation of a public vehicle grant. The vehicle grant, which has been available since the 40th, is a part of the social insurance system. The vehicle grant has been revised several times and the present form was established in the 80ties (SOU, 1982). For a further discussion about the vehicle grant system see (Fulland & Peters, 1999b; HANDU, 1999; Peters, 1998; Ponsford, 2000; Riksrevisionsverket, 1999; SOU, 1994).

5.2 Application of Learner’s Permit

The following description of the process from application of a learner’s permit to driving license and adapted car focuses on the vehicle grant application. The process describes the steps a potential driver with locomotion disabilities has to pass to get a driving license and financial support for an adapted passenger car. The process is described as a flowchart in Figure 3. White boxes indicate decisions taken by authorities and shaded boxes actions required by the applicant. Initially, the applicant has to apply for a learner’s permit at the county administration. Such a permit is mandatory for all learner drivers in Sweden, disabled or not, before any driving can take place. A health declaration, completed by the applicant and duly signed, has to be attached to the application. However, a medical certificate issued by a general practitioner or specialist is needed if the applicant has a disability, which is considered to influence the fitness to drive. The medical requirements for fitness to drive are specified in national directives and amendments issued by the SNRA (Vägverket, 1996b, 1998b)] which are based on the EC directives (EC, 2000; EEC, 1991). There are different types of medical requirements e.g. absence of diseases, sufficient cognitive, perceptual and locomotive ability. The overall principle seems to be to ensure that drivers with disabilities have the same possibilities to drive as safe as any other driver. The SNRA has published a report on traffic medicine which describes details about the fitness to drive assessment in Sweden (Vägverket, 2001). The
medical requirements for fitness to drive are further discussed in next chapter (section 6.7). In Sweden there are virtually no driving assessment centres.

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**Figure 3** The Swedish process from application of learner’s permit to licensed driver with an adapted car for drivers with physical disabilities. The shaded area at the top indicates actions for fitness-to-drive assessment. Shaded boxes indicate actions required by the applicant. Boxes with dotted lines are non-mandatory steps.

There are approx. 20 traffic inspectors in Sweden who have been assigned to handle driving licensing for drivers with disabilities. One of these inspectors will assess the applicant and comment the application and prescribe conditions that apply to the
permit. The conditions can include a list of required vehicle adaptations for the vehicle that will be used for driver training. The inspector may also indicate preliminary restriction codes to be added to the driving license. Since 1996 harmonized community codes are used to describe driving license restriction such as medical reason (e.g. use of glasses, restrictions in time, speed etc.) and required vehicle adaptation (e.g. automatic transmission, hand controls) (EC, 2000; EEC, 1991). Finally, before the learner’s permit is issued the police will check if there are any legal obstructions.

5.3 Application of Vehicle Grant

Once the learner’s permit has been issued the learner driver can apply for a vehiclegrant at the local social insurance office. Financial support is granted under the assumption that the following conditions are fulfilled:

- the disability/ies are of permanent character (predicted to last 7 years or more)
- the disability gives rise to substantial mobility restrictions
- the applicant belongs to a defined target group (age and occupation)

The last condition is specified such that the applicant in principle has to be between 18 and 65 years of age, and needs to drive to get to work or school or has been granted an early retirement pension. Under some conditions the applicant has to be no older than 49. The social insurance committee considers the vehicle grant application. The task for the committee is to decide whether the applicant meets the specified conditions or not. If the decision is positive the local insurance office will further handle the matter. The financial support can be granted in four forms:

1. A basic grant for car purchase up to 60,000 SEK (approx. 6,700 Euro)
2. An additional grant (income related) for car purchase up to 40,000 SEK (approx. 4,400 Euro)
3. Adaptation grants to cover the full cost of the required adaptation (no specified limit)
4. Education and training grant (no specified limit)

Typically, an applicant who fills the basic conditions will get the first and third grant. Depending on the income the second grant can be approved as well. The fourth grant is rarely accepted because the condition is that driving is essential for the applicant’s possibilities to work or get a work. Only 1% of the total resources are used for this form of grant (Peters, 1998). Those who do not fill the conditions for vehicle grant e.g. drivers over 65 can apply for financial support from technical aid centres or investigate other sources.

The applicant is responsible for the choosing and purchasing the car and also requesting financial tenders for the adaptation of the car. If possible three competitive bids should be collected but this is not always possible. Information about necessary and possible adaptation of the car is mostly provided by the adaptation companies. The local social insurance office is responsible for comparing the offers and selecting the
best one. A traffic inspector could be consulted by the social insurance office for advice but it is not mandatory and it happens only in approx. 25% of all cases (Peters & Östlund, 1999a; Riksrevisionsverket, 1999). Finally, the social insurance office decides what adaptation is required and which adaptation company to choose. There are no specific quality requirements that apply when selecting adaptation company (SOU, 1994).

The financial conditions for drivers with disabilities are in relatively good in Sweden compared to most other countries (Fulland & Peters, 1999b; Nicolle et al., 1992). However, during the last years the conditions have drastically deteriorated due to decreased funding from the government. This has led to a situation when grants are approved but cannot be effectuated due to lack of funding. As the vehicle grant is a legal right this is unacceptable. It also creates a difficult situation for the adaptation companies. Detailed analysis of how the vehicle grant resources have been used lately can be found on the internet (http://www.rfv.se/).

5.4 Adaptation and Training

The adaptation work may proceed in parallel with education and training of the learner driver. Training is often done in a provisionally adapted car owned by a driving school. Sometimes it is required that the car is adapted and approved before the training can be carried out. However, this mainly occurs for sever disabilities requiring advanced and individual adaptations. If the applicant’s chances of becoming licensed are very uncertain the training phase may precede the adaptation of the car. In some cases there might also be a need to further assess the applicant’s disabilities and abilities for the adaptation and training. Occupational therapists are quite seldom involved in the adaptation process. This is different from many other countries e.g. the US and UK where driving assessment centres are staffed with therapists who are specialised in driving assessment and vehicle adaptation. There is very little to be found in the regulations and directives to guide the adaptation work apart from the overall objective that the driver’s disability should be compensated. Guidelines or other documented practices are not used in Sweden in contrast to what can be found in e.g. England and Norway (DOT, 1992; SINTEF, 1993). Driver education and training can be performed privately or at a driving school as for all learner drivers in Sweden. Permission to a private instructor can be granted by the county administration if the person is at least 24 years of age and has held a driving license for at least five years. There are no specific requirements, which apply for driving instructors who educate and train drivers with disabilities. This is remarkable as training drivers with disabilities can be very different from what the instructors are used to (Falkmer, Gustavsson, Nielsen, & Peters, 2000). However, the vehicle should be adapted according to the conditions given by the traffic inspector.

5.5 Adaptation Inspection and Driving License Test

Once the vehicle has been properly adapted it has to pass a registration inspection and be registered as adapted by the vehicle inspection. The owner of the car is formerly responsible for bringing the car to the registration inspection. However, many
adaptation companies will have the car inspected and approved before delivery. Today many social insurance offices also require that the car has been approved by the vehicle inspection before they launch the vehicle grant. The compulsory registration inspection covers only technical aspects of the adapted car. It does not consider the adaptation in relation to the driver.

Successful education and training is followed by a theoretical and practical driving test according to Annex II in the EC directives (EC, 2000; EEC, 1991) and as implemented by the SNRA. If the driver fails, further rehabilitation could be an option, which should be investigated before a second continued training and a new driving test. Another reason for an unsuccessful test could be improper adaptation. A license with restrictions as specified by a traffic inspector will be issued by the county administration after a successful driving test. A traffic inspector might do a final evaluation of the adaptation with the driver but this is not mandatory and very seldom done. More details about the process can be found in two surveys made among traffic inspectors and officials at the Social Insurance Offices (Peters & Östlund, 1999a, 1999b).

5.6 Problems with the Current Process

Figure 3 might give the impression that the process is sufficiently organized and structured. However, between eight and ten different instances and even more experts are involved in the process. In this way the process is not optimal and can be experiences as quite complex to the driver applicant (Ponsford, 2000). There is a need for independent information about vehicles and adaptations. Furthermore, the process is fragmented and the communication between the experts involved is not sufficient (Peters & Östlund, 1999a, 1999b). The result of the fitness to drive assessment is not optimally used for specifying vehicle adaptation and driver training requirements. Occupational therapists’ expertise is not sufficiently utilised in the process. There is a need to further develop, validate and standardise tests that can be used for the assessment of fitness to drive assessment. This will be discussed in chapter 6. The social insurance offices have no specific knowledge of traffic safety and vehicle adaptations yet they decide which adaptation the driver finally will get. Certification of adaptation companies have been proposed (SOU, 1994) but it has never been implemented. The routines for registration inspection of adapted cars should be revised (Henriksson & Peters, 2004). Too many cars that are incorrectly registered as either adapted or not adapted. Finally, there is no mandatory evaluation of the adapted car to verify that the compensatory requirements are fulfilled (Fulland & Peters, 1999b). Beyond all these remarks, the financial situation should be reviewed. An extensive cost benefit analysis of the vehicle grant was proposed some years ago (Riksrevisionsverket, 1999).

Several measures to improve the situation have been proposed (Fulland & Peters, 1999b; Peters, 1998), e.g. better information to the potential drivers, let the SNRA administer the vehicle grant, set up driver assessment centres like in the UK, Norway, develop routines that will facilitate information and knowledge sharing
between experts involved, and implement a mandatory adaptation evaluation as a quality check for the driver.

Lately, some initiatives have been taken to improve the situation. A mobility centre is currently (2004) being set up in Gothenburg as an initiative taken by three disability organisations. It project which started last year is financially sponsored by the Swedish Inheritance Fund (SIF) and performed in collaboration with the SNRA, NSIB and the County Administration. For further information see www.mobilitetscenter.se. A handbook is presently (January 2004) being compiled by VTI with information for potential drivers with physical disabilities who need an adapted car. Finally, 2003, a committee was appointed by the government to investigate the vehicle grant system and to propose a revised system during 2004.

5.7 Summary
In summary the following remarks and suggestions for improvements can be made concerning the current situation in Sweden:

♦ The process is too complex and not very “client friendly”
♦ There is a lack of independent information to the clients
♦ The co-ordination between responsible authorities is poor
♦ One authority, preferably SNRA, should have the main responsibility
♦ There is a lack of integrated expertise as a service to the clients
♦ Mobility centres should be set up and evaluated
♦ Occupational therapists with specialise training in driver assessment and vehicle adaptation should be involved in the process
♦ The result of the fitness to drive assessment should be used to formulate adaptation and training requirements
♦ An adaptation evaluation should be developed and tested as a quality control and service to the clients
♦ The vehicle inspection routines for adapted cars should be reviewed and revised
♦ An in depth cost benefit analysis of the vehicle grants systems should be performed as a basis for a revised system
6 From Medical Assessment to Adaptation Evaluation

This chapter discusses principles for the process from initial assessment of a potential driver to the final adaptation evaluation and go into more details compared to chapter 5. On the other hand it is more general as the process is discussed on international (primarily European) level. The process is specifically described and analysed in view of drivers with such impairments that vehicle adaptations are required, e.g. drivers with locomotive disabilities. The person who is assessed is called a client in the following.

6.1 Background and Objectives

As discussed in chapter 4 both mobility and safety objectives should be considered throughout the process from the initial assessment to the final adaptation evaluation. Thus, mobility is the primary objective but safety cannot be neglected. The client can be viewed as a customer of what could be called an automobility (autonomous mobility) service. Automobility was coined by Henderson and Kole (1965). They described automobility as: “a word which connotes not only the realities of the twentieth century where the automobile and geographic mobility are almost synonymous, but to stress that for the disabled, the vehicle should be treated as a prosthetic device necessary for mobility. Thus, the term (automobility) is used in the present context to dramatize the needs of the handicapped for “self-transportability” which goes beyond the use of crutches or wheelchairs.” Subsequently, the overall aim is to provide the right automobility tool for a group of people who have very few alternatives.

The more specific aim of the process is to determine if a person with impairments will be able to drive a car or if other means of transportation should be provided e.g. special transportation services. The possible results of the assessment of fitness to drive process can be divided into the following five cases:

1. fit to drive
2. fit to drive with restrictions in time or space
3. fit to drive with adaptation
4. combination of 2 and 3
5. unfit to drive

The second and the third case are drivers who will have driving license restrictions and this dissertation is specifically concerned with those that require a vehicle adaptation. The focus here will be on case 3.

6.2 From Initial Medical Assessment to Final Adaptation Evaluation

In the following a distinction is made between assessment and evaluation that should be known before going on.
**Assessment** is used to describe the actions taken to identify and determine the range of abilities and disabilities of a potential driver with impairments in order to find out if the person has a potential to become a licensed driver. The assessment should consider both a medical and functional aspects of the potential driver.

**Evaluation** is used for the appraisal actions carried out to verify that the vehicle adaptation fulfills the objective to compensate for the driver’s impairments.

The medical assessment and adaptation evaluation have somewhat different goals. Furthermore, medical assessment focuses on the driver while the adaptation evaluation concerns the vehicle and the adaptation. Figure 4 outlines the process starting with the medical and functional assessment and ending with the adaptation evaluation.

![Diagram](image-url)

**Figure 4** A general outline of the fitness to drive process.
The assessment will determine if the medical and functional preconditions as specified in Annex III in 91/439/EEC are fulfilled (EEC, 1991). If the outcome is that the client can drive if provided with the right vehicle adaptation then the assessment should be translated into vehicle recommendations and preliminary prescriptions for both adaptation and training requirements. The preliminary prescriptions should be used to guide vehicle adaptation, education and training activities. The preliminary prescriptions will most likely have to be revised several times before the final result has been achieved. All revisions should be carefully documented in order to develop the methods and tools used for the assessment.

Once the preliminary prescriptions are available the adaptation and the training can be initiated. The first critical adaptation action is to select a suitable car in order to facilitate the adaptation and to ensure a positive final result. The need for communication between the adaptation engineer and the driving instructor has been indicated with a dual-directed arrow. Once the adaptation is finished the car has to be inspected and approved by the vehicle inspection. All vehicles that are adapted should pass a registration inspection. The driver has to pass a driving license test. Finally, the adaptation evaluation aims to verify that the vehicle has been appropriately adapted and that driver’s disabilities have been compensated. This means that the driver should be given the same possibilities to drive safely as non-disabled drivers in standard production cars. The adaptation evaluation should also confirm that the driver can manage to drive independently i.e. without any assistance.

6.3 A Client Centred Process

The client is in a way the one who knows the nature of his or her impairments best. Furthermore, the client is “owner” of the problem, i.e. not being able to drive a standard production car. Thus, the client’s needs, intentions, attitudes, decisions, and actions etc. are important to consider for the outcome of the fitness to drive assessment. Only the client can determine whether the final result was a success or not. Thus, it is important to involve the client in the process. This will also make it more likely that the client will accept the result of the assessment. The client should be convinced of the benefits with the assessment and trust the assessor. It is also important to make it clear that the assessment aims to determine if driving is a mobility alternative that will be both safe and independent. This has implications both in terms of what is included in the assessment and how it should be done. The necessary assessment actions should be clearly justified to the client and unnecessary assessment should be avoided as this can be experienced as discriminating. The assessment should not be more extensive than needed. Basically, the demands should not be higher for drivers with disabilities than for other drivers and only what is valid for a client’s ability to drive should be assessed. Applying a client centred assessment is there for needed. In practical terms this means that efforts should be made so that the client experiences the assessment as a service. Furthermore, the client should be involved in the adaptation of the car. The adaptation usually needs to be individually fitted.
6.4 **Clients with Different Traffic Experiences**

Clients may have different previous traffic experiences. Clients can be categorised according experiences as:

1. potential drivers with no previous traffic experience
2. potential drivers with previous traffic experience but not as drivers
3. previous drivers with a withdrawn license due to an acquired disability
4. current drivers with a progressive disability requiring a re-assessment

Yet another group can be defined as drivers with cars that were not properly adapted according to their requirements. In this case the matter of concern would not be so much the assessment of the driver as the evaluation of the adaptation. However, complementary assessment may be needed. The four groups are different in such a way that it will influence the assessment process in terms of education and training requirements. For instance learner drivers with no traffic experience will often be people with congenital disabilities who never were able to ride a bike, motorcycle, scoter or similar. They may, however, have some traffic experience as pedestrians. The education and training for this category of drivers should specifically address traffic safety and aiming to develop sufficient risk awareness, e.g. the driver’s perception of risk and its relation to speed changes has to be learned. Control and handling of the car will have to be learned from scratch.

6.5 **The Validity of the Assessment**

One of the primary objectives of the fitness to drive assessment is to determine if the client will be able to drive safely. Thus, the assessment should be both sensitive and specific (see Table 2) and discriminate between those with a potential to become licensed drivers and those that have not this potential. *High sensitivity* implies that the assessment tools will identify all individuals that are able to drive safely. High sensitivity has the advantage that the risk of missing a potentially driver is low but on the other hand will the risk of letting a non-fit driver pass also be high. *High specificity* means that we can effectively distinguish those *not* fit to drive with the risk of increasing the number of missed but fit drivers.

| Table 2 Possible result of medical assessment in terms of passing a driving license test |
|-------------------------------------------|--------------------------|--------------------------|
| **Licensed**                         | **Not licensed**        |
| Potential to become a safe driver possibly with restrictions (fit to drive) | Correctly licensed drivers | Missed capable drivers |
| Insufficient Potential to become a safe driver even with restrictions (not fit to driver) | Incorrectly licensed drivers | Correctly rejected incapable drivers |
A perfect selection mechanism would mean no missed or incorrectly licensed drivers. Even if it is not possible to achieve a perfect assessment tool, the aim should be to simultaneously have a high sensitivity and specificity. The discussion about sensitivity and specificity is actually derived from signal detection theory (Wickens, 1992). Thus, sensitivity and specificity can also be described in terms of ROC (Receiver operating characteristics) curves (Heeger, 1998). However, the terms sensitivity and specificity is more commonly used in the medical domain.

Closely related to the issues of sensitivity and specificity is the question of how valid the assessment methods and tools or tests are in the sense that actually measure the client’s fitness to drive. The methods and tools used to assess fitness to drive should be validated. There is, in general, a lack of validated and relevant assessment methods and tools, which can predict if a driver with disabilities is capable to fulfil traffic safety requirements. For example Christie (1996) reviewed a number of research studies concerned with the assessment of driving capabilities following a brain injury or disease. Christie concluded her report with three recommendations. There is a need for:

- more research on assessment methods with greater experimental control
- further investigation of the relationship between deficits in higher order cognitive functions including personality disorders and the ability to drive safely
- investigating the validity of a driving performance test as an external criterion of safe driving style for brain injured drivers

Reaction time tests have some relevance for a person’s ability to drive but sometimes its value to predict traffic safety is overemphasised. Sanders and McCormick (1993) put it very drastically: “one factor that separates the quick from the dead in traffic is reaction time in emergency situations”. This may be occasionally true but it is far from the whole truth. There is also a need for criteria that can be used as reference for the assessment (Strano, 1997) however there are very few and seems like it very common that the assessor uses subjective criteria (Ranney & Hunt, 1997; Strano, 1997).

### 6.6 Driver Performance and Driver Behaviour

Evans (1991) made a distinction between driver performance and driver behaviour. Driver performance is used to describe the upper limit of a driver’s ability, that is, how good a driver can perform the task at the best. Driver behaviour denotes how the driver is actually driving. Keeping this distinction in mind we can note that even a high performer can exhibit a bad driving behaviour. What matters most, for traffic safety, is driving behaviour. Young drivers are often high performers with respect to some physical abilities such as reaction time, visual acuity, force, and stamina. But their driving behaviour can be of low quality due to inexperience, lack of risk perception or life style. Older and more experienced drivers may have a lower performance but a safer driving behaviour. Degraded performance can partly be compensated for by changes in driving behaviour but to what extent is not fully known. Even a long
reaction time can, partly, be compensated for. As a consequence, performance tests must be used with caution when predicting driving behaviour. In summary, valid performance tests are valuable assessment tools but there is a lack of sufficient valid assessment tools.

6.7 The Medical Assessment of Fitness to Drive

The medical assessment of fitness to drive serves three objectives:

1. discriminate those with a potential to become a licensed driver from those that do not have this potential
2. predict the outcome of a driving test (driving ability)
3. prescribe specific driver training and vehicle adaptation

The medical assessment includes several activities. First of all, the medical assessment should determine the medical status of the client. The EC directive (91/439/EEC) Annex III “Minimum standards of physical and mental fitness for driving a power driven vehicle” provide the medical requirements for the fitness to drive assessment (EEC, 1991). The following three types of medical requirements can be identified in the directives:

1. absence of diseases e.g. epilepsy, diabetes
2. functional requirements e.g. vision, hearing,
3. compensatory requirements e.g. locomotive impairments

Furthermore, the directive prescribes renewed assessment in case of progressive diseases. The medical assessment can include a behind-the-wheel assessment in order to relate the client’s abilities and disabilities to the driving task demands and to provide a functional description of the client’s abilities and disabilities. Thus, the medical assessment includes also a functional assessment. Once the medical assessment is finished a decision should be made if the client is considered to have the necessary potential to become a licensed driver. In case of a positive decision the assessment results should be used to prescribe adaptation and training needs for the client. Details of the medical assessment are discussed in the following.

6.7.1 The Client’s Medical Status or Diagnosis

Establishing the client’s medical status or diagnosis is the first step in a medical assessment. It serves mainly the purpose of a gross discrimination between those fit to drive and those that are not. Thus, this assessment should have a high sensitivity. Those who are falsely let through should be captured later during functional assessment. In some cases it may be important for a client’s willingness to accept that they are not able to drive if they feel that a fair chance was given. Central to the medical assessment is to establish the patient’s diagnosis. The medical diagnosis will provide crucial information about a person’s abilities to drive. Either a specialised physician or a general practitioner, all depending of the type of disability, will carry
out the medical assessment. If a cognitive disability is present a psychological expert should be involved in the medical assessment.

Disabilities are either congenital or acquired. Some disabilities are progressive and some are more or less static over a substantial time period. Acquired disabilities could be either traumatic or caused by a disease. Usually clients have been or still are patients at a rehabilitation clinic. As part of the medical care the patient will be examined and assessed by a physician in order to diagnose the nature of the impairment. The diagnosis will help to classify observed problems, determine appropriate treatment, and prognosticate the future for the patient. The diagnosis can be used as a key to determine what kind of functional disabilities can be expected such as motor, perceptual and cognitive. Thus, the medical diagnosis is a piece of important information for the fitness to drive assessment. It is, however, not sufficient in the sense that it cannot be used in isolation to determine adaptation and training requirements for a potential driver. Different individuals with the same type of medical diagnosis can have different functional disabilities. The key point, when concerned with vehicle adaptations, is to consider the functional disabilities and not the underlying medical causes.

In some cases, the diagnosis will be crucial for discriminating who is capable to drive from a more legal point of view i.e. regulations and directives. Some driving licence restrictions are based on specific medical diagnosis for example epilepsy, and some cardio-vascular diseases (Vägverket, 1996a). In some cases certain abilities are considered essential for driving. Of particular importance is to determine if a person has any visual deficiencies (visual acuity, field of vision, colour vision, double vision, and depth perception). Driving is a visually demanding task and specific regulations have been established in order to verify a potential driver’s visual function. However, the importance of visual abilities is sometimes over exaggerated (Sivak, 1996). Other specific problems as occurrence of spasticity, seizure, and vertigo are important to reveal and document in the medical assessment. The physician can also provide information about prescribed medication and possible implications due to medication. Other issues indirectly influencing the ability to drive include respiration, bladder function, susceptibility to pressure sores, cardiovascular function, and temperature regulation.

Finally, the medical assessment serves includes a medical referral (doctor’s certificate) which is needed in order to get a driver’s permit in Sweden (Fulland & Peters, 1999b). The next step in the assessment process is to link the diagnosis to the functional disabilities and implications for driving.

The WHO ICD (International Classification of Diseases) can be used to provide a standardised medical diagnosis. This is an approach applied in the CONSENSUS project (IST-2001-37092) as the first step in the fitness to drive assessment (Peters, Falkmer, Bekiaris, & Sommer, 2004). The ICD coding is then linked to the WHO ICF (International Classification of Functions) and finally linked to the driving task requirements. The idea is to develop a concise pan-European functional classification.
system, with reference to driving ability as a foundation for an exchange of information within a network of assessment experts. This will be done in order to promote a coherent code of practice on driving ability assessment.

6.7.2 From Diagnose to Functional Disabilities and Abilities

Once the medical diagnosis has been established a number of potential problems can be identified. The initial medical assessment should be translated into functional abilities and disabilities. Functional abilities can be understood as combinations of fundamental abilities which are more task-oriented but still generic e.g. reaction time, co-ordination. This requires a multidisciplinary approach. In Sweden, a physician will conduct the medical assessment and a traffic inspector will make a traffic safety assessment as two separate tasks with little or no communication. In other countries, as in the United States and England, there are driver rehabilitation centres with paramedical experts as physiotherapists and occupational therapists who specialise in fitness to drive assessment (Pierce, 1997). As a help in the assessment process it is useful to have access to some kind of documentation of various diagnoses and their possible implications for the ability to drive and for design of adaptations and training requirements. An example of such a document, from a driving assessment centre in Ruston, Louisiana, is shown below (Havard & Shipp, 1999).

Example excerpt from Ann Havard’s and Michael Shipp’s publication “Disabilities and Their Implication for Driver Assessment and Training” with permission from the authors

Spinal Cord Injury
In spinal cord injuries, the spinal cord is partially or completely severed and there is motor and sensory loss below the level of the injury. With paraplegia, only the trunk and legs are affected and with quadriplegia, the trunk, arms and legs are affected.

Problems

Motor
1. Partial or total loss of muscle control below the level of lesion
2. Spasticity due to exaggeration of normal stretch reflexes
3. Contractures, especially if partial loss occurs
4. Loss of range of motion
5. Decreased breathing if the spinal cord injury is high
6. Loss of balance if trunk muscles are weak or spasticity is present

Sensory
1. Partial or total loss of touch and tactile sense below the level of injury
2. Partial or total loss of sense of temperature
3. Partial or total loss of postural and equilibrium reactions
4. Pain at the level of the injury
5. Diffuse pain below the level of injury
6. Sensory losses may affect normal use and control of muscle movement.

Cognition
1. Cognition is not usually affected directly, although head injuries may also occur in conjunction with the spinal cord injury and affect decision making, problem solving, judgment, vision or perceptual skills.

**Intrapersonal**

1. Loss of sense of independence
2. Fear of becoming helpless
3. Anger or hostility (Why me?)
4. Depression or suicidal thoughts
5. Loss of self-image, especially masculinity or femininity
6. Poor coping skills, especially if skills prior to injury were marginal (Level of education, cultural and social values, and family support structure are variables.)
7. May feel unable to make decisions, solve problems or take responsibility.

**Interpersonal**

1. May withdraw and refuse to interact with friends or family
2. May take frustration out on others
3. May revert to dependency behaviours.

**Implications for driver assessment**

1. The level and extent of the spinal cord involvement will determine the person's need for vehicle modifications and adaptive driving equipment.
2. For the person whose legs are affected, driving from a sedan equipped with adaptive driving equipment may be possible. Adaptive driving equipment might include a hand control, remote horn/dimmer, parking brake extension lever and a steering device. Be sure that you see the person perform the transfer to the sedan and watch them load the wheelchair.
3. For the person whose involvement is so severe that he/she can't independently get into and out of a sedan, an extensively modified van may be the vehicle of choice. If the person needs to drive from the wheelchair, then the driver's station in the van needs to be modified to accommodate the wheelchair.
4. If the person is unable to turn the head, then the mirror system in the vehicle will have to be expanded so that the person can see the roadway behind them as well as to their sides.
5. Visual-perceptual and cognitive abilities may be impaired if the brain as well as the spinal cord were involved during the accident. Therefore, functional visual perceptual and cognitive assessments should be done.
6. The person may have difficulty reaching and/or operating the primary and accessory controls due to loss of range, strength, or contractures of the arms. Therefore, functional range of motion and strength measurements should be taken.
7. In the higher levels of spinal cord injuries, trunk control is often affected. You should evaluate the need for trunk support (i.e. custom seating system, Grandmar strap, lateral supports on the wheelchair, etc.) Wheel chair and custom seating systems should only be changed by medical professionals (therapists) to accommodate postural, muscle and sensory needs and not adversely affect other life functions.

**Implications for driver training**

1. Many of these people have driven previous to their injuries, so they may just need time to adjust to the new equipment. The higher the level of injury, the more time is needed to learn the high tech equipment. However, since most spinal cord injuries are caused by motor vehicle accidents, the person may have a poor driving record or history of high risk behaviour.
2. With high tech vehicles, training should be done in the person's modified van with the equipment set specifically for them.
3. People with high level spinal cord injuries usually have decreased energy levels and endurance. So you may need to have shorter training sessions.
4. People with high level spinal cord injuries can't regulate their body temperatures. Adjust the temperature control before the person gets in the vehicle and maintain temperatures to prevent overheating or reactions to the cold
5. Lower extremity spasms may cause interference with or inadvertent activation of the brake and gas pedals and may require pedal blocks or special strapping
6. Medication may interfere with the alertness of the person driving. Check to see what medication he/she is on.

7. Provide training tasks to challenge balance.

As can be seen from the example above, this kind of documentation provides valuable information about a specific diagnosis. A short description is given about the disease. Then a number of relevant problems are listed. The problems are grouped in to five categories: motor, sensory, cognitive, intrapersonal, and interpersonal. The first three are of specific interest to the assessment requirement and the last two for the driving training and driving behaviour. Finally, some significant implications for adaptation and training are provided. However, the information is not detailed enough for a prescription of adaptation and/or training requirement, but it provides some general insight about the character of the disability. What we do know from the description above is that SCI is an impairment that will first of all affect motor and sensor ability. Thus, it will be important to assess e.g. range of motion, force in the limbs, trunk stability and endurance. There is an increased risk for spasticity and contractures. Usually there are no cognitive impairments but the assessor should be observant. Medication should be considered also for the assessment. Furthermore, it can be seen that climate control in the car may be important to consider during the assessment.

From this example it becomes obvious that there is a need for a detailed assessment. The assessment should be documented for the prescription of adaptation. A good help would be to have standardised assessment forms. In the UK a plethora of assessment forms is being used but efforts are made to develop standardised forms. Before prescribing adaptation and training requirements it is useful to perform what is often known as a "behind-the-wheel assessment" in a provisionally adapted car. Such a practical assessment is even prescribed in the EC directive (91/439/EEC).

### 6.7.3 Behind-the-wheel assessment

Driving instructors and examiners often claim that the best test for assessing fitness to drive is to perform an on the road assessment. The behind-the-wheel assessment is the practical assessment of specific functions that are needed in order to be able to drive a car. The behind-the-wheel assessment can be understood as a test of functional abilities in context, e.g. “Are the co-ordination of psychomotor abilities sufficient to control a car?” The car has to be reasonably adapted but the adaptation does not have to be as perfect as the final adaptation. The assessor must be able to discriminate between different sources of observed problems during the test drive. The objective is to predict the client’s potential to drive despite the disabilities and to fulfil traffic safety requirements. In other words, the task is to assess the chances that the disabilities can be compensated for by vehicle adaptation and/or training. Problems that can be revealed during a test drive can be caused by:

- the test situation (stress, anxiety, etc.)
- insufficient adaptation
- lack of training/experience
- the driver's disabilities
In order to provide a fair test situation, the driving instructor should strive for a relaxed and natural situation in which the driver may forget the actual assessment purpose of the test drive. Today there are no widely used standardised driving tests for this purpose but many driving instructors and organisations have developed their own test methods. The reliability and usefulness of this kind of assessment would be greatly improved if a standardised driving test were developed, validated and used. The result of a behind-the-wheel assessment depends also on the individual driving instructor’s knowledge and experience. Thus, it is important that the assessor is properly educated and trained. Such an education should also consider social skills. In general, a behind-the-wheel assessment should address the following aspects of the driving task: steering control, braking control, accelerating control, and caution/safety awareness (Bolduc, 1999). For each of these aspects, there are several subtasks that need to be considered. This could be exemplified for the steering control task. Steering control assessment should include a judgement of the driver’s ability to:

- maintain correct hand position on steering device
- keep within lane without weaving or unintentionally touching lane boundary
- turn without cutting
- recover correct heading after a turn
- make correct left/right lane change
- maintain steering control even on rough road texture

These subtasks were derived from a seminar on Driving Controls for High Level Disability at the ADED (Association of Driver Educators for the Disabled) conference which took place in Louisville 1999 (Bolduc, 1999). Depending on the driver’s disability/ies some of the assessment steps and aspects might be irrelevant and some more crucial. That is to say that the test needs to be flexible in order to adapt to the individual client. The test could preferably begin on a closed test track and then continue on a road with low traffic. If possible it could be of value to cover various traffic environments as residential, urban, rural, and highway roads. The assessor should use a scale when rating the performance. A good idea is to let the driver repeatedly perform tasks and subtasks and then make an initial and a final rating of the performance. This will give information both on learning/training ability and possible endurance problems. The assessment should be done in a structured way and the results of included subtasks should be recorded in a protocol. For instance CBR in the Netherlands use the TRIP (Test Ride for Investigating Practical Fitness to Drive) protocol adapted to different disabilities for the behind the wheel assessment. The TRIP protocol was developed by Wiebo Brouwer et al. at University of Groningen in co-operation with CARA and CBR (Raedt & Ponjaert-Kristoffersen, 2000). Finally, the client’s risk awareness is crucial to determine during the assessment, as low awareness may be very difficult to overcome even with extended training and experience.
6.7.4 Prescription of Adaptation and Training Requirements

Once the necessary assessment tests have been performed and documented the results should be used to prescribe provisional adaptation and training requirements. All the collected assessment information could be of value for the prescriptions.

The prescriptions can serve several purposes, but the major one is to feed into the adaptation and training phase of the process. The adaptation prescription can also be used as a specification of requirements to request financial tenders from adaptation companies. In order to serve this purpose the specification of requirements should be given in functional terms and not in terms of specific products. However, it happens that a fitness to drive assessment concludes with a recommendation of a specific adaptation products. This can save time but in the long run have a negative influence on the demand to develop of new adaptation products.

A draft example of an adaptation prescription form based on functional requirements can be found in (Peters, 2001c). Several sources were used as input to this proposal such as the functional classification of car adaptation devices made by SINTEF (SINTEF, 1991, 1992a, 1992b), the driving license condition coding system in Sweden (Vägverket, 1996a, 1998a, 1999) and the classifications of driving aids made in the TELAID (TEEmatics Applications for the Integration of Drivers with Special Needs) project (Naniopoulos & (eds.), 1992). The prescription form co was made up with the following main headings:

- vehicle recommendation
- adapted entrance (ingress/egress)
- assistance for storage of wheelchair and luggage
- adapted seating
- transmission - Adapted gearbox control
- adapted braking control
- adapted acceleration control
- adapted steering control
- adapted secondary control devices (i.e. controls which should be possible to operate while driving e.g. direction indicator, head light, light on/off, wiper/washer, horn)
- control of other functions of vital importance (i.e. controls which need not be operated while driving e.g. ignition, climate control, vision enhancement, etc.
- other requirements

A Swedish version of the adaptation prescription form can be found in a report describing a draft proposal of an adaptation evaluation method (Peters, Fulland, Falkmer, & Nielsen, 2000).

There are some guiding principles that could be applicable for the adaptation prescription. Koppa (1990) proposed three basic requirements for vehicle adaptations to be considered for drivers with physical disabilities:
1. Ingress and egress - the driver should be able to enter and leave the car without assistance
2. Primary and secondary controls - the driver should be able to operate the car without assistance at the same performance level as an able-bodied driver under all traffic conditions
3. Occupant safety - the driver should be provided with the same level of protective safety as drivers of standard production cars.

Prescriptions of training requirements are seldom used. Driving instructors could derive information from the behind-the-wheel assessment, if it was accessible. However, they usually rely on their own judgement and experience possibly supplemented with a new behind-the-wheel assessment. A prescription of training requirements would in several aspects be different from an adaptation prescription. The theoretical education and practical training aim at a conveying knowledge, insight and skills to the learner driver. The driving instructor’s task is to guide a learner driver through the learning process in order to become a licensed driver. Inter- and intrapersonal factors have implications for the driver training as shown with the previous example of possible implications for a client with SCI. The same example also illustrates more specific training concerns like medication, endurance and climate concerns. Such information can be very useful for the instructor. The prescriptions for training and adaptation should be considered together as there can be adaptations that can facilitate the training e.g. foldable pedals and there might be some adaptations that require specific training considerations e.g. joystick controlled driving. This will be discussed in relation the adaptation evaluation. The education and training prescription should also consider that learner drives are also different with respect to their experience as discussed in section 6.4. Learner drivers with previous experience of the traffic are likely to have developed an awareness of traffic risk. Thus, training efforts can be devoted to vehicle handling and integration with previous traffic experience. Learner drivers with previous driving experience may have to unlearn some well-learned (automatic) behaviour. Experienced drivers exhibit a lot of automatised skills when driving. This can sometimes make relearning and retraining complicated and time consuming. Occasionally specific adaptation equipment could lessen the risk of or even prevent erroneous behaviour. Consider for instance a driver who has to learn to drive with a left foot accelerator pedal after being used to drive a standard production car. Additional adaptation, e.g. foldable pedals, can in this case be of great help. Unlearning automatized behaviour can be more difficult than learning new skills, especially for those with a long experience of learned behaviour. In conclusion it is importance to know what previous experience a client has of the traffic environment and how this experience was gained. The training period for a driver with disabilities can be substantially longer compared to a peer learner driver without impairments. In a retrospective study of learner drivers with cerebral palsy it was found that these drivers on average had 2.7 times more lessons compared to those without any disability (Falkmer, Henriksson, Gregersen, & Bjurulf, 2000). Education and training for learner drivers with disabilities is extensively described and discussed in an EC report compiled in a Greek-Swedish project called HORIZON (Falkmer, Gustavsson et al., 2000).
6.8 Adaptation and Training

Once the medical and functional assessment have been concluded the actual adaptation of the vehicle and the driver training can start. Vehicle adaptation will be extensively discussed later while driver training will not be considered at any length as this is beyond the scope of this dissertation. However, a few words about the communication between the driving instructor and the adaptation engineer. Much of the training and adaptation work is made ac hoc and intuitively. Furthermore, the actual decisions and considerations made are seldom documented, which means that there is an obvious risk that “silent” knowledge will be lost. Technical documentation of the adaptation is usually provided and even requested for the vehicle inspection but this does not say all there is to know about the adaptation process. Driving instructors usually document the education and training for all learner drivers but this is not always adapted to suit learner drivers with disabilities. Falkmer et al. (2000) have shown how documentation of driver education can be used to investigate educational problems for learner drivers with cerebral palsy. The adaptation of the vehicle and the driver training can sometimes be done in parallel i.e. the driver training is not done in the client’s own car. In this case it is important that there is a close communication between the driving instructor and the adaptation engineer. Furthermore, a formal prescription of adaptation and training requirements can also serve the purpose to encourage the communication between adaptation specialists, driving instructor and even involve the client and other persons or institutes involved.

The overall objective for the adaptation is to compensate for the driver’s impairments which are important for driving. Even if the requirements specified by Koppa (1990) seems to be rather basic (see 6.7.4) there are probably very few adaptations, which completely fulfil them. For instance the occupant safety requirement can turn out to be impossible to fulfil for a driver who does not have the physical strength to withstand the forces from safety systems like airbags and safety belts. Furthermore, drivers with disabilities might have fewer resources available for the driving task, which means there is an obvious risk to overload the driver. Overload can severely affect preventive traffic safety. Drivers with disabilities are often consciously aware of their resource limits and behave accordingly when they drive. However, there is a risk that they will be closer to their performance limit – which means that they perhaps will drive at a higher “cost” in load (Peters, 2001b; Sprigle, Morris, Nowachek, & Karg, 1995). This should be considered when implementing the adaptation and in the final evaluation of the adaptation (Strano, 1997).

Apart from Koppa’s list of basic requirements, presented above, there are other aspects that should be considered e.g. a paresis conditions could cause problems with body temperature regulation and an AC (Air Condition) system can be indispensable in order to provide an acceptable climate. A defroster device might be necessary for people living in a cold climate. In an emergency situation the driver may need to call for help. Finally, service and maintenance are also aspects that should be reckoned.
Any automotive workshop can adapt cars for drivers with disabilities in Sweden. However, a mandatory certification for adaptation work has been proposed several times (e.g. (HANDU, 1999)) even in an official report from the department of social affairs several years ago (SOU, 1994). Neither the SNRA nor the vehicle inspection has published any specific regulations for how car should be adapted to drivers with disabilities. However, all adapted cars should pass a registration inspection before they are used with a few exemptions for some simple adaptations. Furthermore, there are even no national guidelines for adaptation of cars in Sweden. Other countries like England, Norway, and The Netherlands have published guidelines for adaptation of car controls (DOT, 1992; Kempeneers, 2000; SINTEF, 1993). The application of the three R’s (Reduce, Reinforce and Replace) is a general adaptation guideline applied in The Netherlands (Kempeneers, 2000). The idea is to: Reduce the driving task load e.g. use automatic transmission, Reinforce available abilities e.g. use servo assisted steering, Replacement or modification of controls e.g. use left foot accelerator or manual service brake. The following are some examples of more specific guidelines for the adaptation of primary controls that have been applied in England and Norway (DOT, 1992; SINTEF, 1993):

- the force needed to operate the accelerator should be limited to 10% of maximum strength
- the force needed to operate the brake and clutch should be limited to 30% of maximum strength for normal driving conditions, emergency braking can require more but well within the individuals max. capacity
- the required steering force should be between 10 - 30% of maximum strength depending on driving condition

These recommendations were largely based on research made at the Cranfield University by Kember (1991). But there is need for more elaborated guidelines.

Some general vehicle standards, regulations and directives can also be useful as guidance on how to adapt cars e.g. the European steering and braking directives (EEC, 1970, 1971). In the US the SAE has issued some guidelines for adapted cars (Pierce, 1997). However, there are rather few directives that apply to adapted cars (Fulland & Peters, 1999b; Veenbaas & Brekelmans, 1996). Guidelines on how to design and utilise transport informatics applications, e.g. Intelligent Transport Systems (ITS) is also needed in order to ensure that those who might benefit most from these support systems also can use them (Hakamies-Blomqvist & Peters, 2000; Ranney, 1997). This was a subject that is also discussed in paper II (Peters, 2001a) and paper III (Nicolle & Peters, 1999).

6.9 Evaluation of the Adaptation

The final step in the fitness to drive process will be to evaluate the adaptation with respect to the driver’s disabilities. The objective for this step is to find out if the adaptation sufficiently compensate the driver’s disability and make optimal use of the available resources.
Such an adaptation evaluation is rarely done and it is not specifically prescribed in any EC country even if the EC directive (91/439/EEC) indicates that the adaptation should be evaluated with the driver. However, the directive is not very specific in this case. In case the adaptation is evaluated, the evaluation is seldom structured and almost never documented (Fulland & Peters, 1999b; Peters & Östlund, 1999a, 1999b). A draft proposal of an adaptation evaluation method was developed at VTI in order to overcome the identified problems (Peters & Falkmer, 2004; Peters et al., 2000). The perspective applied in the proposal was rather broad and several aspects of the adaptation were included in the evaluation. In more detail, the drafted method considered four factors for the evaluation: protective safety, preventive safety, discomfort and trust. The evaluation is done in five steps (see Table 3). The factors that should be considered for each step are indicated in the table with an “X”. The first two steps focus on protective safety factors. The two following steps, manoeuvre test and general driving, are specifically aimed to evaluate the driver’s control of the car i.e. preventive safety. The evaluation of preventive safety and vehicle control will be discussed in more detail later on. As can be seen from Table 3 discomfort should also be evaluated in the manoeuvre test and during general driving. This should be understood as seating comfort and stability should be investigated in the part of the adaptation evaluation which includes actual driving. The final evaluation is a summary of all the previous steps.

Table 3 The five steps included in the drafted adaptation method and four evaluation factors. The Xs indicate the factors that should be considered in each step.

<table>
<thead>
<tr>
<th>Evaluation step</th>
<th>Protective safety</th>
<th>Preventive safety</th>
<th>Discomfort</th>
<th>Trust</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Stationary vehicle no driver</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. Stationary vehicle with driver</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>3. Manoeuvre test</td>
<td></td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>4. General driving</td>
<td></td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>5. Final evaluation (summary)</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

The proposed evaluation method constitutes just a framework and more detailed guidance is needed for the evaluation. As an example we can list some requirements that should be addressed in the adaptation evaluation. The adaptation should allow driver to:

- be able to reach all controls needed to operate the car
- have sufficient force to operate all controls even in an emergency situation
- be able to react fast enough (reaction performance) in an emergency situation
- be able to apply and maintain a sufficient force to operate controls in an emergency situation (endurance)
- co-ordinate control actions
- drive with a low risk of getting spastic cramp attacks

Verwey (1994) listed a number of issues that should be considered when evaluating adapted cars for drivers with spinal cord injuries:

- the risk of overloading the upper limbs as too many tasks have be performed with these limbs
- the risk of interference between control tasks
- super light controls can require continuous corrections which could be very tiring
- control-by-wire controls may suppress relevant feedback to the driver
- mental load can be affected by the in-output relation of the control function
- there is a risk that the design of controls may prevent the driver from distributing available resources to prevent overload

In summary it can be seen that there is a need to develop methods and tools that can be used to evaluate the adaptation in relation to the driver. It was proposed that a checklist should be compiled to document the driver’s opinion together with objective tests like brake and steering performance included in the draft evaluation method (Peters et al., 2000). Subjective aspects that should be included are experienced functionality, comfort and the driver’s trust in the adaptation. The adaptation evaluation should also consider workload aspects. Furthermore, the adaptation evaluation should provide an answer to the question “Will the driver be able to drive with sufficient safety margins?”. The concept of safety margins will be discussed in the following chapters.

6.10 Expertise Needed in the Process

One final concern in relation to the fitness to drive process discussed above has to do with the question of who will perform the different assessment and evaluation tasks in the process. The various tasks are very different and multidisciplinary expertise is required including medical, paramedical, traffic safety, driver training, adaptation technology and possibly more. This means that there can be experts with different disciplinary background but their expertise should directed to driver assessment, rehabilitation and traffic safety. It seems feasible to adopt the approach to set up training programs for certifying driving rehabilitation specialists as done e.g. in the US (French & Hanson, 1998; Kalina, 1997). The assessment should be performed as a team work (Pierce, 1997) which can also include cooperation between researchers and driving rehabilitation specialists (Ranney & Hunt, 1997). The team approach will also minimise the risk that safety aspects neglected. Much information and knowledge needs to be communicated, shared and integrated and the mechanisms to support this need to be further developed. For example prescriptions for adaptation and training are seldom used and this probably affects the communication between professionals involved in the process (Fulland & Peters, 1999b). Finally, the client should be actively involved in the process as discussed in 6.3.
6.11 Summary

In summary, the fitness to drive process from the initial medical assessment to the final adaptation evaluation should:

- be designed so that it is experienced as a service to the client
- actively involve the client in the process
- accurately discriminate between those fit to drive and those not fit
- be based on methods and tools that are validated or possible to validate
- include an assessment that is both predictive and prescriptive
- include an adaptation evaluation which considers the driver
- be comprehensive and based on multidisciplinary expertise
- be organised to facilitate communication and integration of expertise
7 Drivers with Disabilities, Vehicle Adaptation and Driver Behaviour Models

This chapter consists of a review of different driver behaviour models with regard to drivers with disabilities and vehicle adaptations. Driver behaviour models will be discussed in relation to different phases of the process from fitness-to-drive assessment to vehicle adaptation evaluation with a main focus on the last phase. The presentation aims to exemplify how driver behaviour models can be used to describe and analyse driving and vehicle adaptation. The focus is limited to the actual driving, i.e. the driver’s control of the car or in other words preventive safety. Thus, e.g. ingress, egress, maintenance, wheelchair handling and other non-driving aspects will not be considered. Finally, comfort, trust, driver opinion, workload and protective safety are not directly addressed either.

7.1 Driving as a Cognitive Task

Driving a car is complex in the sense that it requires that the driver uses a wide range of abilities in order to interact with a complex environment and manage the task demands. Driving is dynamic as the demands can vary from very low to extremely high within fractions of a second. When the demands are high the driving task needs to be carried out in a force-paced fashion while when the demands are low it can be performed in a self-paced manner. Normal driving can be considered as a dynamically changing combination of force-paced and self-paced behaviour.

This thesis focuses on the part of the driving task that concerns vehicle handling i.e. steering and speed control. This restricted view is not meant to reduce driving to a set of isolated low level skills. Instead, driving is considered as a cognitively motivated, regulated and controlled task. Cognition is here used in the pragmatic sense as defined by Neisser (1976), i.e. cognition in context and not as an internal mental activity of knowledge (i.e. “the acquisition, organisation and use of knowledge”). The motive for this cognitive stance can be found in Michon’s (1985) visionary discussion about driver behaviour modelling “…the distinctly hierarchical cognitive structure of human behaviour in the traffic environment …”. However, the cognitive approach does not mean that perceptual and psychomotor abilities should be neglected. This approach has been applied e.g. in adaptive control models, control theory and cognitive systems engineering in order to model driving. Thus, driving is viewed as a cognitive task of control in a context perceived through the senses and changed with psychomotor actions.

7.2 Classifying Driver Behaviour Models

A theoretical model can be used to describe the driving task, the demands on the driver and the actual driver behaviour. Driver behaviour modelling can also be of help to understand how different impairments can affect driving performance and behaviour. Driving is probably one of the most demanding, dynamic and complex tasks that
people regularly carry out. However, driving is most of the time a simple and not very demanding task for an experienced and skilled driver. But all drivers are not skilled and experienced even if they have passed a driving test and the driving task demands can change from very low to extremely high. These are some of the plausible reasons why driving has received quite a lot of attention also from a theoretical perspective.

The task of driving have received a lot of attention and over the years several theories and models of driver behaviour have been presented, applied, analysed, criticised and abandoned. Two different approaches have been used to describe driving. The first is to model what drivers actually do when they drive and the second is to describe what the drivers should do by modelling the driving task itself. The first can be called a behavioural approach and the second a normative approach. This distinction will be used when discussing some models later. Different models often emphasise specific and sometimes different aspects of driver behaviour e.g. accident causation, education and training, behavioural adaptation. So far, no all-purpose, generic, comprehensive, and verifiable model of driver behaviour has been presented (Ranney, 1994). Probably, there will never be one partly because if it is comprehensive it will be too shallow or if it is deep it will be too specific or too complex. However, instead of searching for the perfect model it seems more constructive to build a network of different models linked together in a more generic framework. Thus, it can be useful to categorise existing models in order to get a more structured view of existing driver behaviour models (see e.g. (Alm, 1989; Michon, 1985; Ranney, 1994; van Winsum, 1996; Vogel, 2002)). Models have been categorised in view of specific research questions e.g. effects of traffic safety measures (Vogel, 2002), accident causation (Alm, 1989) and driver behaviour changes (van Winsum, 1996).

Michon (1985) made a more generic classification of driver behaviour models, using a two-way classification. In the first place he distinguished between behavioural or input-output oriented models and internal state or psychological models. What Michon actually meant with internal state was motivation or the “reason for moving”. Thus a more suitable label would be motivational. Secondly he differentiated between functional and taxonomic models.

<table>
<thead>
<tr>
<th>Behavioural (Input-Output)</th>
<th>Taxonomic</th>
<th>Functional</th>
</tr>
</thead>
<tbody>
<tr>
<td>Task analyses</td>
<td>Adaptive control models</td>
<td></td>
</tr>
<tr>
<td>Internal State (Psychological)</td>
<td>Trait models</td>
<td>Motivational models</td>
</tr>
</tbody>
</table>

Taxonomic models are inventories of isolated facts while functional models specify components of driver behaviour and their dynamic relations. Task analysis based models decompose driving into tasks and subtasks and relate them to driver
requirements and abilities. This type of model will be exemplified with a model developed for driver education and training by McKnight & Adams (1970a). Trait models are based on the idea that it is possible to identify the accident-prone driver with the use of well-designed tests. This approach will be exemplified by the work done by McKenna (1982). Functional models differ from taxonomic in that they connect model components in order to consider the dynamics of driver behaviour e.g. hierarchical structures. The servo-control model developed by McRuer et al. (1977) to describe drivers’ steering control is an example of adaptive control models that will be discussed in rather detail in relation to adaptation evaluation. Motivational models consider internal states as attitudes, subjective risk, insight as controlling factors and will be exemplified with risk-driven behaviour models like the Zero risk theory (Näätänen & Summala, 1974) and risk reducing models like the GDE (Goals for Driver Education) framework with focus on driver training (Hatakka, Kesikinen, Gregersen, Glad, & Hernetkoski, 2002). In the following discussion about different models reference will be made to this two-way classification of driver behaviour models.

So far it seems like no driver behaviour model has specifically addressed drivers with disabilities and the need for vehicle adaptation. In most models the interface between the driver and the vehicle (e.g. steering wheel, pedals, etc.) is considered as given and not adaptable. Driver behaviour models which specifically address adaptation are mostly concerned with the adaptable human i.e. driver behaviour changes. However, there are several models which can be useful when concerned with drivers with disabilities and vehicle adaptations as will be shown. The process from the initial medical fitness assessment to the final adaptation evaluation as discussed in chapter 6 can be divided into three steps:

1. medical and functional assessment of fitness-to-drive
2. prescription of adaptation and training/education
3. evaluation of vehicle adaptation

These steps have a bit different objectives and the following discussion about driver behaviour models will be done in view of these three steps.

### 7.3 Medical Assessment and Driver Behaviour Models

The first step, *the medical and functional assessment*, aims to predict a candidate's possibilities to become a safe, licensed driver. The medical fitness assessment should thus ensure that the candidate have the abilities needed to drive with or without adaptation. Some of the functional abilities used by a driver are depicted on a conceptual level in Figure 5. Basically we can distinguish three types of abilities: cognitive, perceptual, and motor.
Figure 5 Overview of functional abilities used by a driver.

The three types of abilities in Figure 5 can be broken down into several functions, which are used while driving. In the medical assessment it can be essential to measure these functions and combinations of functions in detail as discussed in chapter 6. Sometimes it is easier to set up requirements in terms of absence of certain diagnosis or diseases but basically the aim is the same as for the functional requirements to ensure that the driver have certain abilities. The last requirement, compensation, is a way to open for alternatives but the basic requirement is that the driver in the end should be able to driver equally safe as any other driver without disabilities. The medical assessment should also feed into the prescription step. This can be done by identifying impairments that need to be compensated for and residual abilities that can be used to compensate. Although, progressive conditions, fluctuating abilities and medication, will not be dealt with here it must be understood that they bring complicating factors to driving ability assessment and that it is necessary for a framework for the fitness-to-drive assessment which can link abilities to driver performance.

7.3.1 Differential Accident Involvement, Individual Differences and Trait models
A distinction can be made between performance and behaviour as mentioned in section 6.6. Driver performance is not a reliable predictor of accident involvement (Evans, 1991) but in the fitness-to-drive assessment it can be highly relevant to consider performance as a measure of what the driver can do at the best.
Substantial research efforts have been devoted to understand the relationship between human abilities, driving performance and accident involvement. Much of this work was conducted as epidemiological studies of accident causation. This research is often referred to as the study of differential accident involvement (McKenna, 1982). The idea was that some drivers are more likely to be involved in crashes than others and that psychological tests could be used to identify accident-prone drivers. Thus, accident proneness is considered to be a stable personal trait that can be measured. The models emerging from this research are known as trait models (e.g. (McKenna, 1983)). Trait models are taxonomic models applying a psychological or motivational view of driver behaviour (see Table 4). However, the research based on the idea of accident-prone drivers has not been successful in generating a reliable and comprehensive theory on which a method to assess fitness-to-drive could be based. Ranney (1994) even proposed that the differential accident involvement paradigm should be abandoned. There are several plausible explanations to the lack of success: human diversity, human flexibility and often a fragmented view in which isolated abilities have been linked to driving performance consequences to mention a few. Llaneras, et al. (1993) conducted an extensive literature review covering fourteen human abilities in the context of driving performance (i.e. static visual acuity, contrast sensitivity, useful field of vision, field dependence, depth perception, glare sensitivity, night vision, reaction time, multilimb co-ordination, and physical proficiency, control precision, decision-making, selective attention, and attention sharing) and elderly drivers. Most of the abilities investigated were perceptual or cognitive. The authors concluded that driver abilities are critical components of the vehicle-driver-roadway system. However, different abilities seem to interact in a complex manner and contribute to the overall performance. Thus, it is likely that no single ability measure can be used to predict driving performance (Llaneras et al., 1993). Even if Llaneras et al. (1993) had a focus on elderly drivers their conclusions are relevant also for drivers with disabilities in general (Galski, Ehle, & Williams, 1998; Sprigle et al., 1995). How functional abilities contribute, interact and can replace each other to promote safe driver behaviour has not been captured in any driver behaviour model so far. The driving task is also very complex and the demands on the driver can vary from very low to extremely high. In addition, bad performance can have fatal consequences. All this makes it very difficult to completely map human abilities to driving performance and accident involvement (Ranney, 1997).

However, it can be a useful approach to predict driver performance by investigating certain abilities, when considering specific driver groups like older drivers and drivers with disabilities, and specific abilities like vision, reaction time, and divided attention. Missing, impaired abilities will influence driving performance, some more than others. If we first consider psychomotor abilities, which are generally not considered when criticising the skill models, it is obvious that lack of force, reach etc. certainly will limit the driver’s possibilities to operate a car e.g. (Asmussen, Poulsen, & Sorensen, 1964), (Lings, 1990). Degraded perceptual abilities, like lack of dexterity, hearing and vision will also affect the driver’s ability to drive (Lings, 1991). Finally, cognitive impairments also affect driving performance. Lundqvist et al. (1997) found that tests that measure cognitive capacity can predict driving performance with good reliability.
for drivers with a brain lesion. However, the understanding of how human abilities and adaptation contribute to driving performance has to be further developed. It is too early to definitely abandon the skill models when considering drivers with specific impairments. Christie (1996) concluded that there is a need for more empirical work in order to better understand how to assess cognitive disabilities. It should also be noted that we don’t know very much about how different abilities interact and if missing abilities can be compensated. Finally, it should be noted that current skill models do not consider situational factors like changing task demands and driver experience, which play an important role in explaining traffic accidents.

The *trait* model approach is applied in the EC driving licence directives. As discussed above, driving requires a range of human abilities. Maybe the most obvious, crucial and easily measurable ability needed for driving is vision. Vision has acquired a lot of attention and this can also be seen in the driving licence regulation as the requirements for traffic vision are far more detailed than requirements for other abilities. Undoubtedly, driving is a visually demanding task but there are a number of other abilities beyond vision needed in order to drive successfully e.g. cognitive abilities like decision making, attention etc. and manual control using hands and feet. Furthermore, successful driving requires combinations of abilities, which adds to the complexity of the task. This complexity of both task and behaviour points to the questionable approach to use performance tests developed in controlled laboratory environments in a fitness-to-drive assessment. There is a risk that such assessment will be out of context and not catch the critical combinations of abilities needed when driving. Sometimes, specific tests can be relevant but it seems like they cannot replace a practical driving test. So even if the *trait* models can be useful for the medical assessment of drivers with disabilities their usefulness is limited. Test scores cannot sufficiently reliable predict crash involvement. This problem can be attributed to a lack of an underlying theory of crash causation (Ranney, 1997).

Bekiaris et al. (2003) just recently presented a model called *DRIVABILITY* which might resolve some of the problems with *trait* models by (e.g. considering the environment, applying a holistic view in which different abilities are linked together). *DRIVABILITY* is defined as a combination of permanent and temporary factors which will determine driver performance. The authors propose the use of an index based on individual resources, knowledge/skill, environmental factors, risk awareness and workload. One application proposed for this index is fitness-to-drive assessment. However, so far this model has not been tested even if the authors suggest how it can be applied for different purposes e.g. assessment of temporary or permanent driver impairments. However, what is interesting with this new concept is that it tries to overcome some of the known limitation with current models relevant for driver assessment.

### 7.4 Adaptation Prescription and Driver Behaviour Models

The objective of the second step, prescription, is to provide information on how to adapt the vehicle and train the driver. The adaptation objective is to compensate for the
driver’s disabilities so that the driver will be able to perform the driving task just as well as any other driver without disabilities. In this step the result of the medical assessment should be translated into adaptation and training requirements. In order to do this it is e.g. necessary to rank available abilities so the available abilities are optimally used. This requires a holistic view and long experience. In practical terms this could be formulated as a "rule of thumb", e.g. the strongest limb should be used to operate the brake lever or the limb with best range of motion should be used for steering control. However, such proverbs can only be applied with great caution and not “mechanically”.

7.4.1 Taxonomic or Descriptive Models

First, a description of the driving task is needed in order to relate the task and its components to the driver’s abilities. Taxonomic models are also called descriptive models. The most well known example of taxonomic models is the task analysis based model developed by McKnight and Adams (1970a) (1970b) (1970c). This model was developed for driver education purposes and describes what the driver should do. The purpose was not to understand what drivers actually do – driver behaviour. The taxonomic approach gives a fragmented and static view of the driving task but it could be useful when trying to identify potential problems that a driver with disabilities might have to face with a specific vehicle design. Tasks and subtasks should be matched to the driver’s abilities. This approach was used in an inventory made to identify requirements for drivers with different disabilities in the TELAID project (Nicolle et al., 1992). A total of 11 principal tasks, 73 sub-tasks at the next level, and 165 sub-tasks called prompts at the lowest level were identified. It seems possible to use the taxonomic approach in order to develop a prescription form in which adaptation requirements could be specified for an individual, at least to a certain extent. Such a form was compiled in the project on which most of this thesis is based (Peters, 2001c; Peters et al., 2000). This form included 11 main headings e.g. selection of car, adaptation of primary and secondary controls. The idea was to provide a means for transferring the medical assessment results into adaptation specifications. However, this form has never been tested. Finally, the taxonomic models could be of some help in the prescription phase even if they suffer from the same limitation as the trait models; they do not consider the context and the dynamic interaction between driver behaviour components.

7.4.2 Motivational Models

Driver training prescription requires an understanding of how skills and knowledge are acquired. The driver behaviour modelling was for many years occupied with trying to explain traffic accidents e.g. trait models. The individual difference approach and the trait models failed to provide better understanding of the underlying factors in traffic accidents. Furthermore, it did not consider situational factors. The shift to motivational models emphasised risk and situational factors and was a reaction to the skill models. The motivational models are functional models, which capture some of the dynamic relations between driver behaviour components (see Table 4). Three of the most well known motivational models are the Risk Homeostasis Theory (Wilde, 1982), the Zero Risk Theory (Näätänen & Summala, 1974) and the Threat Avoidance Model (Fuller,
Wilde’s Risk Homeostasis Theory is based on the assumption that the level of accepted risk is a rather stable individual parameter. The driver controls the vehicle in accordance with a subjective target risk. An implication of Wilde’s approach is that all actions taken to improve safety will be neutralised by the driver. The consequences of Wilde’s theory have led to considerable controversy and the theory has been rejected by several researchers (e.g. (McKenna, 1982; Michon, 1985; Sanders & McCormick, 1993)). Van Winsum (1996) claimed that this debate for some time stalled the progress of motivational theories. The Zero Risk Theory (Näätänen & Summala, 1974) differs from the Risk Homeostasis Theory in that the driver is assumed to accept no risk at all, i.e. the target risk is zero. Or rather that risk is not a primary controlling factor that can be used to predict driver behaviour. The driver’s subjective risk monitoring is essential for the Zero Risk Theory. The best traffic safety measures will be those that decrease objective risk but increase subjective risk. However, most of the time subjective risk will be zero. This is a contradiction in the model, which was addressed by Fuller (1984) in his Threat Avoidance Model. There are two problems related to the Zero Risk Theory, the dissociation of subjective and objective risk, and subjective risk as a regulator mechanism even though the subjective risk is zero most of the time. However, Summala (1985, 1988) later replaced the concept of subjective risk in favour of safety margins as a driver control mechanism. Fuller formulated the Threat Avoidance Model with the ambition to overcome the problems associated with the Zero Risk Theory (Fuller, 1984). The Threat Avoidance Model is more a theory of learning applied to driving. The driver is controlling the vehicle in order to avoid threats or risky situations. A distinction can be made between drivers who avoid threats by anticipatory driving and those who react to threats by delayed avoidance. Learner drivers are more likely to make delayed avoidance compared to experienced drivers. Hazard detection ability, also referred to as hazard cognition, becomes critical for driving performance and has by some authors been related to accident involvement of young drivers. In conclusion it also seems like the motivational models failed to generate testable hypothesis (Michon, 1989; Ranney, 1994). Furthermore, these motivational models fail to consider the fundamental cognitive structure of driver behaviour as pointed out by Michon (1985). However, the shift from the subjective risk concept to safety margins and uncertainty as proposed by Summala (1988) can be used to explain control shift from automatic to conscious processing as discussed by both Ranney (1994) and van Winsum (1996).

7.4.3 Hierarchical Control Models
Before continuing with driver training curricula and driver behaviour models we need to consider the cognitive view of driving. Central to the behaviouristic approach developed by e.g. Skinner and Watson was the concept of Stimulus-Response (SR) theory (Solso, 1991, page 67). The idea was that human behaviour could be explained in terms of a response to stimuli. The basic idea was that human behaviour is pure response to perceived stimulus i.e. a more or less hardwired coupling between perception and action. In this view cognition becomes implicit and the focus was on observable behaviour. The SR theory was based on the assumption that cause is a prior condition that determines future effects. The basic stimulus – response mechanism in SR theory was also applied input-output models developed as a reaction to the
behavioural approach e.g. SRK (Skill-, Rule-, Knowledge-based behaviour) and HIP (Human Information Processing) models.

A useful model should be able to predict driver behaviour in general and driver risk behaviour. If that is not possible, hypothesis based on the model cannot be falsified and consequently not tested. Most models, discussed above, can only offer post hoc explanations of observed behaviour or possibly explain aggregated accident data (Rumar, 1988). Furthermore, much of the modelling, e.g. the trait models, have been occupied with traffic accident causation but what is needed is to know more about everyday risk free driver behaviour. Early cognitive models focused on information processing and driving was viewed as a problem-solving task (Rumar, 1988). Accidents were attributed to incorrect information processing. Rumar concluded that there was an urgent need to develop models and hypothesis that can predict actual driver behaviour (Rumar, 1988). Michon (1985) claimed, some years earlier, that the lack of progress emerged from the failure to consider results from cognitive psychology. More recent models incorporated developments from cognitive psychology, e.g. hierarchical control structures and automaticity (Ranney, 1994). Rumar (1988) pointed out that an important behavioural uniqueness of driving can be its combination of consciously controlled (cognitive) and unconsciously, automatic (perceptual) behaviour. The modelling debate went on during the 80’s. Michon (1985) advocated the idea of hierarchical control models in his critical review of driver behaviour models which would resolve some of the identified shortcomings with previous models. It is interesting to note that this was not a new idea Allen et al. (1971) and later McRuer et al. (1977) and Janssen (1979) described driving as a hierarchical structured task with strategic, tactical and operational components demanding different levels of driver control long before this was widely accepted. Michon (1985) refers to Jansen (1979) when describing the hierarchical structure of the driving task (see Figure 6). At the strategic level, the driver is concerned with tasks such as planning the journey, selecting the mode of transport, and choosing a route. At the manoeuvring level, the tasks concerned include overtaking, giving way to other vehicles, and obeying traffic rules. At the control level, the driver is concerned with controlling the vehicle, e.g. controlling speed, following the road, and quite simply keeping the car on the road. There is a communication between the three levels where goals and criteria are defined at a higher level and the outcome of lower levels modifies goals at a higher level.
Michon (1985) finally meant that a comprehensive model of driver behaviour should not just identify different levels but also provide a control structure which enables control to shift from one level to another in timely manner.

Given the hierarchical description of the driving task it should be matched to actual human behaviour. Human control structures are highly flexible and highly dependent on practice and experience. These structural aspects of human performance were addressed in the hierarchical SRK (Skill-, Rule-, Knowledge-based behaviour) model developed by Rasmussen (1986). Rasmussen identified a number of cognitive functional elements organised in a three-layered structure. The model discriminates between skill-based, rule-based and knowledge-based control. The main issue in Rasmussen’s framework is the hierarchical nature of human control replacing the serial model used in early models of human information processing (see Figure 7). The SRK model has been extensively used to model driver behaviour. However, the SRK model is fundamentally a SR model and does not explicitly consider context (e.g. the operator’s interaction with the system to be controlled) or time (Hollnagel, 2002b).
The hierarchical control model takes into account both the task structure and the human control structure by combing the two frameworks mentioned above (Ranney, 1994). For example Michon (1985) combined the SRK behavioural model with a hierarchical structure of the driving task and compiled a matrix that have been used to e.g. explain driver behaviour and to identify driver support needs (Michon, 1993; Nilsson, Harms, & Peters, 2001; Ranney, 1994) (see Table 5).

Table 5 A hierarchical control model considering both task structure and human control structure (Ranney, 1994)

<table>
<thead>
<tr>
<th>Driver behaviour</th>
<th>Strategic Level</th>
<th>Manoeuvring Level</th>
<th>Control Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Knowledge-based</td>
<td>Navigating in unfamiliar area</td>
<td>Controlling skid</td>
<td>Novice on first lesson</td>
</tr>
<tr>
<td>Rule-based</td>
<td>Choice between familiar routes</td>
<td>Passing other vehicles</td>
<td>Driving unfamiliar vehicle</td>
</tr>
<tr>
<td>Skill-based</td>
<td>Route choice for daily commuting</td>
<td>Negotiating familiar intersection</td>
<td>Vehicle handling in curve driving</td>
</tr>
</tbody>
</table>

Driver training advances can be depicted as a shift from knowledge based behaviour for all task levels towards rule-based and skill-based behaviour for the tactical and operational task levels. In the case of training drivers with disabilities it might also be a matter of forgetting earlier automatised behaviour. Learner drivers with disabilities can be of three different categories: those with previous driving experience, those with no driving experience, but with traffic experience; and those with no traffic experience. Drivers with previous driving experience may face problems of forgetting (de-learning) and re-learning, e.g. left foot accelerator for leg amputees. This type of problems can be described and studied with help of the hierarchical control model. Much of what used to be automated skills might have to be performed as knowledge based behaviour to begin.

Even if time constraints are not specifically addressed in the hierarchical control model time requirements are different for the three task levels. The following approximate time frames apply: 10 seconds or more for the strategic level, between 1 and 10 seconds for the tactical level, and less than 1 second at control level. Finally, it should be noted that more complicated driver tasks e.g. an overtaking manoeuvre may require knowledge-, rule- and skill-based actions. It is not simply the time requirements that distinguish the different levels of tasks, but also the requirements of attention, workload, and the consequences of mistakes, etc. The hierarchical control model is a functional model, which does not specifically include motivational aspects and should be classified as an adaptive control model.

7.4.4 The GDE Framework: Integrating Hierarchical Control Models and Motivational Models of Driver Behaviour

The hierarchical control model does not consider individual differences, which are likely to influence the individual development of skill and knowledge during driver
Individual differences should be considered in driver education and training curriculum (Hatakka et al., 2002). The need to consider personal preconditions in both fitness-to-drive assessment and training prescription was exemplified in chapter 4 (the multiple sclerosis case). Motivational models of driver behaviour ‘propose a general compensatory mechanism whereby drivers adjust their driving (e.g. speed) to establish a balance between what happens on the road and their level of acceptable subjective risk (Ranney, 1994). The idea that drivers compensate for risks by adjusting their subjective risk levels, which is a fundamental assumption in motivational theories, indicates that drivers’ personal motives and preconditions are likely to determine what the individual considers as safe driving behaviour. For this reason, a fourth level corresponding to individual dispositions was added to the hierarchical structure of driver behaviour in the GDE (Goals for Driver Education) Framework (Hatakka et al., 2002). The top level “Goals for life and goals for living” of the GDE model refers to personal preconditions and ambitions in life and was assigned the highest priority as personal dispositions heavily influence driving behaviour at lower levels (vehicle handling). The GDE framework is usually described as a matrix with driver behaviour hierarchy as four horizontal levels (rows) and the vertical dimension is divided in three columns assigned to driver training and motivational aspects (see Table 6). There is no hierarchical connection between the columns as there is between the rows. The first column (knowledge and skills) considers driving task demands, which in the hierarchical control model were divided, into three task levels. Thus, in the GDE framework it was merged into one level. The second column concerns risk perception as a controlling factor in driver behaviour. The view applied to risk as a controlling factor in driver behaviour was inherited from other motivational based theories (e.g. (Fuller, 1984; Summala, 1985)). The third column addresses the role of the driver’s meta-knowledge about his/her own limits of skills, subjective risk level, personal behaviour and attitudes etc. The cells in Table 6 contain examples derived from the description given by Hatakka et al. (2002).

Table 6 The GDE framework as a matrix (adapted from Hatakka et al. (2002))

<table>
<thead>
<tr>
<th>Hierarchical level of behaviour</th>
<th>Knowledge and skills</th>
<th>Risk-increasing factors</th>
<th>Self-evaluation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Goals for life and skills for living (general)</td>
<td>Life style personal preferences</td>
<td>Acceptance of risk</td>
<td>Awareness of risk tendencies and impulse control</td>
</tr>
<tr>
<td>Goals and context of driving (trip related)</td>
<td>Trip goals and planning</td>
<td>Driver state and social context</td>
<td>Awareness of own driving motives</td>
</tr>
<tr>
<td>Mastery of traffic situations</td>
<td>Traffic rules</td>
<td>Wrong expectations driving style</td>
<td>Awareness of own driving style</td>
</tr>
<tr>
<td>Vehicle manoeuvring</td>
<td>Vehicle handling</td>
<td>Insufficient automatism and skill</td>
<td>Awareness of automatism and skill</td>
</tr>
</tbody>
</table>

As the GDE framework was specifically aimed at driver education and training it should be suitable also for training and education of drivers with disabilities. However, the GDE framework focused very much on risk perception and young risky male
drivers. Subsequently, GDE addressed the problem that improved skills will not always reduce risk and stressed the need to consider risk-increasing factors and self-evaluation in driver education and training. In the case of drivers with disabilities we also have to consider lack of confidence together with overconfidence. This means that the GDE framework should be adapted accordingly. However, the idea to consider personal dispositions as done in the GDE framework should be highly relevant also for drivers with disabilities.

7.5 Adaptation Evaluation and Driver Behaviour Models
The objective in the third and final step, *adaptation evaluation*, is to verify that the adaptation requirements are satisfied and to investigate if the provided adaptation will allow the driver to drive with sufficient safety margins. Thus, the safety margin concept as proposed by e.g. (Ranney, 1994; Rumar, 1988; Summala, 1985; van der Hulst, 1999; van Winsum, 1996) will be discussed in relation to driver behaviour modelling and vehicle adaptation evaluation.

7.5.1 Human Information Processing Models
Both mental and physical load can be a problem in vehicle adaptation and even lead to performance breakdown. The SRK model, which is basically a SR model, does not tell us much about why we sometimes fail in our control of the car. This was addressed in an approach, which considered the human operator (e.g. a driver) as an information processing system (MacKay, 1956). Mental workload and resource limitations are the specific main concerns in Human Information Processing (HIP) models. The HIP model developed by Wickens (1992) explained some driver behaviour phenomena e.g. failure to react to available information and attributed the phenomena to limited attention resources (see Figure 8). Attention resources have to be shared between perception, cognition and actions (Wickens, 1992). Attention serves like an executive control of perceptual, cognitive and action resources.

![Figure 8 The Human Information Processing (HIP) model (from Wickens, 1992)](image-url)
Matching driving task components to the driver’s abilities in view of the HIP model will help to identify problems and to decide how the available capacity in terms of attention, perception, cognition and action resources can be used best (Shiffrin & Schneider, 1977; Wickens, 1992). An adaptation should make optimal use of the driver’s available resources (in terms of attention as well perception, cognition and action) in order to minimise the physical and mental load on the driver (Verwey, 1994). This means that when choosing which resource (e.g. left or right hand, speech, blowing/sucking) to use for what type of control it is important to consider the nature of the controlling task to be carried out with the selected resource. If the task is continuous with intermittent high loads like steering then it is important the limb used can withstand continuous loads without risk that the driver becomes spastic. First priority would be to use upper or lower limbs for steering, gas and brake. Resources more suited for intermittent tasks of short duration and possibly with higher cognitive demands (less need to automate) can be used for secondary tasks which are less time critical as controlling head lights, directions indicators etc. In conclusion it is important to consider automated behaviour, interference, resource allocation, workload distribution when prescribing how available resources should be used and to evaluate an adaptation. However, even the HIP model is basically an “SR model” and does not specifically consider the operator’s influence on the environment e.g. the system to be controlled. The HIP model is also limited to reactive or compensatory driver behaviour and does not consider proactive or anticipatory behaviour. Furthermore, in the HIP model the different abilities are viewed as isolated or decoupled entities with unidirectional links.

7.5.2 Control Theory

Before continuing to the adaptive control models a few words about control theory which is fundamental to control models. Control theory or cybernetics Wiener (1948) is a general theory aimed to understand self-regulating systems (Carver & Schreier, 1982). Closely related to cybernetics is General Systems Theory (GST) (Bertalanffy, 1968). The birth of control theory and general systems theory can be dated back to the first half of the previous century and has been applied in a wide range of sciences. The systems view approach applied in cybernetics and GST distinguishes itself from the more traditional analytic approach by emphasising the interactions and connectedness of the different components of a system. The basic control theory idea is simply based on a Stimulus-Response loop. The current system status is compared to a reference value and the deviation between current system status and reference determine the control action. However, the definitions of system boundaries and the relation between cause and effect is different from e.g. information processing models. These differences will be discussed in the following. Control theory have been used to describe and study a wide range of systems from “pure” technical to biological systems and social systems.

A system is an abstract construct, used to identify the focus of interest (Jagacinski & Flach, 2003). The system is also sometimes contrasted to the environment. A system typically refers to the phenomenon of interest and the environment to everything else. When there is a sharp boundary between the system and the environment the system is
considered as a closed system. In this case the environment does not influence the system or it can be disregarded. In a closed system the control is well defined and deterministic. This closed systems view have been applied in human information processing models when the controller (e.g. driver) is considered as a closed system and the controlled object (e.g. car) belongs to the environment. The rational to this approach was to divide human behaviour into isolated entities (e.g. sensation, perception, decision, and action) which could be studied independently (see Figure 9, top). As can be seen it is a closed system (detached from the environment) and the control is an open-loop, i.e. there is no feedback depicted from the controller’s output to system input. This detached and deterministic approach was inherited from natural science and Newtonian physics in particular.

![Diagram](image)

Figure 9 The information processing view (top) and control theory view (bottom) adapted after Jagacinski and Flach (2003)

However, the demarcation between a system and the environment is often not that sharp. Or rather there are phenomena that cannot be explained with this closed systems view. This is specifically true when concerned with behavioural and biological sciences where the relationship between an observer/controller and the environment seems to be of prime importance in order to understand complex phenomena like behavioural adaptation. Cybernetics and GST was developed in an attempt to provide a framework to study these kinds of phenomena and applied much more of a probabilistic view. When the demarcation between a system and the environment is floating or vague the system is considered to be an open system. In open systems the relations between the system and the environment play an important role. All socio-technical systems can be viewed as open systems (Flach, 1999). The primary difference with previously discussed SR models is that control theory considers the operator’s influence on the controlled object and the system boundaries are defined so that both operator and controlled object is included. This open system view is more consistent with an ecological view (Gibson, 1966). Depending on the focus the system boundaries can be very tight to all embracing.
The open system view can be depicted by restructuring the information processing view by closing the loop and putting the environment in the centre (see Figure 9 bottom). By closing the loop the cause – effect relation between stimulus and response loose its meaning. In a closed loop system the stimulus and response are tightly linked and there is no clear distinction what is cause and what is effect. This restructure was done in order to illustrate that the stimuli are as much determined by the actions as the actions are determined by the stimuli (Jagacinski & Flach, 2003). In this way we have a closed loop open system, as the environment is included and the interdependencies between the controller and the environment is considered. This view can be useful when modelling driver behaviour and in particular driver behaviour adaptation.

Cognitive Systems Engineering (CSE) put cognition in context by applying an overall systems view. CSE decompose complex tasks along two dimensions abstract – concrete and whole - part (Jagacinski & Flach, 2003). In this way the focus is shifted from internal functions of either humans or machines to the external function making up a joint cognitive system including both the controller and the controlled system (Hollnagel, 2002a). In this way the driver will be viewed as a controlling system and the car as a technical system to be controlled. In this perspective the car will constitute the primary context for the driver. As more of the context is included the system will expand as a multi-layered functional description. The system boundaries have to be defined according to the purpose of the analysis.

The two most important concepts in Control Theory are the open/closed system and the open/closed loop control. Flach and Jagacinski (2003) among others have further developed the concepts of control theory. Their latest book aimed at providing some quantitative tools based on control theory that can be used to capture and understand also qualitative aspects of human performance e.g. driving behaviour (Jagacinski & Flach, 2003).

7.5.3 Adaptive Control Models

Adaptive control models are concerned with questions about how the driver adapts his control to the characteristics of the system to be controlled (driver – vehicle – environment). Two categories of adaptive control models can be distinguished servo-control and information flow control models (Michon, 1985). The first type models address continuous tracking tasks while the second deals with tasks where discrete decisions are made. The information flow control model found its basis in computer science and symbol processing computer program languages. The dichotomy between continuous (analogue) and discrete (digital) control has more or less lost its meaning due to tremendous increase in computer power (Michon, 1985). However, both views can be used complementary in order to understand some aspects of manual control. For example, firing the motor neurons is a set of discrete all-or-none response. While the motion of an arm depends on the integration over many neurons and can best be described as continuous at a coarse time scale. Early servo-control models were mostly used to study compensatory (feedback) steering control performance on roads with varying curvature and for evasive manoeuvres. McRuer et al. (1977) questioned this
way to model steering behaviour, as it did not consider the anticipatory control which seems to be a behaviour needed in order to understand skilled driving behaviour.

McRuer et al. (1977) proposed a three level servo-control model of drivers’ steering behaviour (see Figure 10). First of all they described driving as consisting of a hierarchy of navigation, guidance, and control phases conducted simultaneously with visual search, recognition and monitoring operations. They also distinguished between closed-loop (compensatory) control and open-loop (anticipatory) control. The compensatory steering control is shown in the lower part of Figure 10 as two feedback loops. The lateral position is fed back and compared to the desired path and if there is a deviation it will result in an error correction action which is compared to current heading angle and eventually result in a steering wheel correction if needed. The perceived road curvature derived from visual input guides the pursuit control. Pursuit control is an open-loop feed-forward control element which permits the driver to follow the anticipated road curvature. An interesting third concept is the precognitive control (Figure 10 top), which in practice is a first phase of dual-mode control, i.e. both open and closed-loop control. Precognitive control consists of previously learned control actions, which are triggered by situation and vehicle motion but work as pure open-loop control.

![Figure 10 A three-level servo-control model of steering (from McRuer et al., 1977)](image)

In view of this model steering can be viewed in terms of output as either a position, velocity or acceleration control system (Jagacinski & Flach, 2003). If the front wheel angle is considered to be the output then the steering system can be approximated as a position control system with a gain given by the steering linkage. While, if heading angle is viewed as the output then steering can be considered as a rate control system. In this case the gain is proportional to the velocity of the front wheels. Finally, if lateral position is considered as the output then steering can be viewed as an acceleration control system. Then the effective gain between steering wheel angle and lateral position is proportional to the square of the velocity. This shows that lateral and longitudinal control of the car is not independent but very much entwined.
Even if McRuer and his colleagues (1977) described driving as a hierarchical task they concentrated very much on the control task. They largely considered driving as a closed system and disregarded the environment except road geometry. Michon (1985) cited Reid (1983) who concluded that the servo-control model described above cannot successfully cope with driver tasks other than following straight and smoothly curved roads. The model needs to be better integrated with the guiding visual environment as described by e.g. Gibson (1966). Michon concluded that “The two fields – perception and vehicle control – are still lacking a theoretical integration. Combining them would constitute a major breakthrough,.....”.

7.5.4 Cognition in Control

The models discussed so far do not explicitly consider context and time, which are critical aspects in driving. First, let us consider context. Most of the models discussed so far are basically mechanistic, as they do not recognise the need of higher order cognitive abilities. The interaction between the driver and the environment is not explicitly included in the model but rather seems to be an implicit presumption. A useful model needs to be better connected with the context. The lack of context in cognition was addressed by Neisser in his book “Cognition and Reality” (Neisser, 1976).

Neisser’s starting point was to criticise Gibson’s idea of direct perception. Neisser (1976) meant that seeing is not just perceiving but also interpreting and understanding on a conscious level. Visual perception is guided by our cognitive model of the world. Meaningful perception requires cognitive structures (models of the world) that can be used to guide and interpret what we perceive. This is also true when we consider the human as a driver. Neisser described a mechanism for transferring retinal images into conscious interpretations and models of the world. Visual perception is processed in several steps until it is transformed to conscious knowledge of the world. Neisser (1976) proposed a cognitively driven model of perception, which includes the interaction between the observer and the environment. He introduced what he called anticipatory schemata that prepare and control our perception. He meant that perception is a constructive process and the perceiver is in each moment constructing anticipations of certain kinds of information. This view can also explain phenomena like illusions, errors, and how we can convey 3D information in 2D displays. Neisser called his model the perceptual cycle.

Neisser (1976) further meant that also control works in a way similar to perception. He meant that in order to control a system the controller has to have a model of the system to be controlled. The importance of a control-guiding model can also be understood in the light of “The law of requisite variety” (Ashby, 1956), which states in principle that the variety of the controller should match the variety of the system to be controlled. The same principles are central to what has become known as “cognition in the wild” (Hutchins, 1995). The idea is to capture the controlling cognitive models used in natural settings. Thus, the controller’s understanding of the system that is being controlled will determine the actual control actions. In other words the driver’s mental model of the vehicle, other drivers, road condition etc. will determine the driver’s
control behaviour. Hollnagel (2002a) described a cyclical model of control, based on the principles of Neisser’s perceptual cycle and included action and control. This approach was in line with the control theory (Wiener, 1954). Hollnagel’s cyclical control model was used as the basis for the Contextual Control Model (COCOM), which describes in general terms how performance depends on perceiving feedback events, interpreting and modification of current understanding, selection and execution of actions (Hollnagel, 2002a).

Driver control behaviour can be described as shown in Figure 11 This figure was based on Hollnagel’s cyclical model of control, COCOM. The control cycle is divided into three phases: perception, decision and action. The control cycle is cognitively initiated by the driver depicted with the arrow coming out of the driver’s head. The driver’s mental model of the vehicle will guide the search for information about the current situation during the perceptual phase. The perceived situation is compared to a reference value defined by the driver. The comparison is followed by a cognitive phase. During this phase a decision will be made, based on the difference between reference value and current situation, i.e. the error. The aim will usually be to minimise the error. This cognitive phase is followed by an action phase during which an appropriate action is selected and carried out. This action influences the environment depicted by the outward arrow. Once the action is carried out the driver searches and perceives the effect of the action together with possible external events and the circle is closed. The result of the action phase is also fed back to the driver and will change the driver’s mental model of the control loop and the system under control. In other words it is the result of the driver’s actions which will form and develop his/her mental models. The three phases are described as three distinct entities but in reality the phases might be overlapping and not separated as might appear from the figure. However, in principle the three phases are different in character. This model of driver control provides a foundation to capture the dynamics in driving e.g. compensatory closed-loop and anticipatory open-loop driving which will be the topic of next section.

![Diagram of the cognitive control cycle](image)

**Figure 11** The cognitive control cycle adapted from Hollnagel’s (2002a) Contextual Control Model
In relation to the discussed control model it can be interesting to consider the dual control problem the driver should both identify the system status and at the same time control it (Jagacinski & Flach, 2003). This could mean that driver occasionally has to get out of control in order to maintain control. This was described by (Weinberg & Weinberg, 1979) as the fundamental regulator paradox:

“The lesson is easiest to see in terms of an experience common to anyone who has ever driven on an icy road. The driver is trying to keep the car from skidding. To know how much steering is required, she must have some inkling of the road’s slickness. But if she succeeds in completely preventing skids, she has no idea how slippery the road really is. Good drivers, experienced on icy roads, will intentionally test the steering from time to time by ‘jiggling’ to cause a small amount of skidding. By this technique they intentionally sacrifice the perfect regulation they know they cannot attain in any case. In return, they receive information that will enable them to do a more reliable, though less perfect job” (cited in (Jagacinski & Flach, 2003))

7.5.5 Compensatory and Anticipatory Control in Driving
Normal driving constitutes a combination of compensatory and anticipatory behaviour. The combination of compensatory and anticipatory driving is context and driver dependent. In a complex traffic situation the driver will have less time to allocate to anticipation and will drive in a more compensatory manner. An inexperienced driver will drive in a more compensatory manner compared to the experienced driver. Anticipatory driving can offload the driver as the driving be more planned and there will be less need for time strained reactive driving. Thus, the driver usually strives to balance between compensatory and anticipatory driving. This can also be viewed as a balance between force paced and self past driving. If e.g. the vehicle controls are not sufficiently adapted according to the driver’s abilities then driving is likely to be carried out in a compensatory manner. This reduction of anticipation can be caused by difficulties in perceiving and interpreting the feedback, deciding what to do or execution of an action. Therefore, time is critical for the overall performance of the joint system driver-adaptation-car. Time is needed to carry out the control cycle. The available time will determine the driver’s safety margins i.e. the driver’s margins to make corrective actions. Time and safety margins will be discussed in the following.

7.5.6 Driving within Safety Margins
Driving is a task that is carried out in time and space. Gibson and Crooks (1938) described driving as a task of controlling the car within the field of safe travel. They defined the field of safe travel as “an indefinite bounded field consisting, at any moment, of the field of possible paths which the car may take unimpeded”. It is an imaginary dynamic area in front of the vehicle with a shape of an outstretched tongue (see Figure 12). Obstacles in the terrain mainly determine the boundaries in the field. Thus, once more, time and space seem to be critical aspects to consider when modelling driver behaviour and Gibson and Crooks’ model provides a foundation for the concept of safety margins and a guiding mechanism for normal safe driving behaviour.
Both van Winsum (1996) and van der Hulst (1999) explored the concept of the safety margins in their thesis. Van Winsum (1996) focused on lateral control while van der Hulst (1999) concentrated on longitudinal control. Van der Hulst meant that experienced drivers have a mental model about the driving task and expectations about what will occur in which situation. A consequence of this is that the driver can effectively scan the traffic environment. The mental model and the expectations will allow the driver to build up and preserve situation awareness and also to take advantage of a precognitive control as described by McRuer et al. (1977). Furthermore, driving is a complex task that can be solved in many ways and will provide opportunities for behaviour adaptation. The driver can choose between several driving strategies. This is a view that can help to better understand the mechanism behind the anticipatory behaviour. Van der Hulst (1999) also meant that driving is a task that allows for pace adjustments by speed and safety margin adjustments. The driver’s choice of speed and safety margins will determine the time available to react to relevant changes in the environment. Van der Hulst thereby connected Gibson and Crooks’ “field of safe travel” with the Ashby’s “law of requisite variety”.

Summala (1985; Summala, 1988) proposed that safety margins could be operationally defined as distance or time related measures like Time-to-line-crossing (TLC) and Time-to-collision (TTC). The concept of safety margins can also be used to explain, at least partly, accident causation. In-depth accident studies have shown that late detection is a very common explanation given for collisions (Rumar, 1988). Late detection can be described as violation of safety margins.

7.5.7 Time and Time Again
Time constraints can be incorporated in the cognitive control cycle (Hollnagel, 2002b). Driving is motion in time and space. Thus, speed, road geometry, obstacles in the field of travel, sight conditions among a range of other factors determine the time the driver can use for the control cycle. This time is labelled $T_u$ (usable time). Hollnagel divided
the control cycle in three different phases: perception, decision and action (see Figure 11). The times needed to carry out these phases are labelled $T_p$, $T_d$, and $T_a$ respectively. In “normal” driving $T_p + T_d + T_a$ is less than $T_u$ (see Figure 13).

During anticipatory driving $T_u$ will be much greater than $(T_p + T_d + T_a)$ but as the difference decrease driving becomes more and more compensatory. If the total usable time is not sufficient, performance will start to degrade. The control becomes more erroneous or sluggish and oscillatory (Jagacinski, 1977). Reducing speed is one way to gain time and control. The model also depicts that the reason to deteriorated performance can be of three types. The cause can be prolonged evaluation or selection or action or even a combination of the tree. In any case the result will be that the used time will be more than the usable time. All three phases are connected, meaning that if one part requires less time than expected then there will be more time for the remaining two phases. When the traffic demands are low and the driver is experienced evaluation, selection, and even action require little time and there will be plenty of time available.

Time pressure is in this view a critical component of driving behaviour when determining the driver’s safety margins. Closely related to this is the concept of uncertainty. The driver will try to minimise uncertainty in order to maintain pace control and safety margins. Uncertainty and lack of anticipation will make drivers vulnerable to accidents.

The time concept in the control cycle described above can also be applied in vehicle adaptation evaluation. For example if the adaptation does not provide sufficient feedback to the driver, then extended time might be needed to evaluate current system status. Remember that driving performance is not just dependent on visual input as we use on wide range of sensory input for the control e.g. force feedback via control devices. Secondly, prolonged time for selection of correct actions can be caused by interference e.g. a coupled lateral and longitudinal control function. The controlling device does not guide the driver to the right action and the driver is likely to need
additional time to select the right action. It might even turn out that the driver has to make an incorrect action in order to gain information needed for the evaluation. The feedback gained by doing incorrect actions can provide valuable information that can help the driver to improve performance. In control theory, the problem of balancing the need to reduce error and the need for information is called the dual control problem (Flach, 1999). Finally, the driver might have to deal with situations when there will be substantial time lags in the system under be controlled. E.g. the driver can move a joystick lever faster than the steering system can react. Similar phenomena can be found with some manual brake controls where the lack of force in the driver’s arm has been compensated for by longer travel path of the control lever. This is a problem that was identified in a recent manoeuvre test with adapted cars (Curry & Southall, 2002). The adaptation problems described above can of course not be attributed to just one phase of the control loop. It is rather a combination of all three phases.

### 7.5.8 Multiple Levels of Control

The SRK model, distinguished three hierarchical levels of driver behaviour skill-based, rule-based and knowledge-based. However, the CSE approach focuses on different levels of a joint system (driver-vehicle-road-traffic etc.) performance rather than internal cognitive processing (Hollnagel, 2002a). Driving also means that the driver has to perform several tasks or subtasks in parallel, e.g. lateral and longitudinal control, secondary tasks together with the primary control. Concurrent activities can be described as corresponding goals at different levels (Hollnagel, 2002a). These activities are of an anticipatory, compensatory or mixed type. The Extended Control Model (ECOM) was developed by Hollnagel in order to consider these aspects of joint system control.

Hollnagel distinguished four hierarchical levels of control; controlling, regulating, monitoring and targeting, with targeting at the top level and controlling at the bottom. These four levels correspond to the levels distinguished in a generic decision model. But he also pointed out that there is no absolute reference that can be used to determine the number of levels needed for all cases. Rather he meant that the purpose is to model performance and the number of levels should be sufficient to fill the purpose. Thus, there can be fewer or more levels. For instance Powers identified 11 levels in his Perceptual Control Theory (Powers, 1998). The levels in Hollnagel’s model should not be considered as distinctive but more as continuous and overlapping.

Hollnagel (2002a) characterised in short the four levels in ECOM as follows. The basic level controlling includes activities needed to keep the vehicle within a time-space continuum with rather tight time limits. Control on this level is performed in an automatic compensatory manner. Activities at the next level, regulating, also concerns vehicle control but in a more anticipatory manner even if the control is basically carried out as closed-loop control and thus needs little attention e.g. anticipatory steering and secondary controls. Activities on the next level, monitoring, includes e.g. monitoring vehicle travel path, monitoring instruments, looking for road signs. These activities are conducted in a more open-loop manner and could be compared to McRuer’s pursuit control. Monitoring does not include closed-loop vehicle control but
rather concerns the joint driver-car system relative to obstacles in the driving environment. At the top level, *targeting*, the driver will e.g. prioritise among short-term and long-term goals. The goal decision at the top level will lead to sub-goals and activities, which can be performed at a more automatic level. The main advantage of the ECOM in comparison to other hierarchical control models is that the different levels are connected. For instance goals are determined at higher levels and applied at lower levels and lower levels provide input or feedback to higher levels. The long-term goal of getting to the destination under time pressure can for example change the goals on other levels. Feedback from lower levels will contribute to form and develop the driver’s mental models of how to control the car. Ranney (1997) meant that even if the cognitive skills are important it is the lower-level psychomotor skills that are the foundation for safe driving. Thus both cognitive and psychomotor skills are needed for safe driving and furthermore the integrations and communication between the skills. It seems like the ECOM can be used to analyse and better understand how different disabilities can influence driving performance and thus be used to develop a useful method for adaptation evaluation.

The approach applied here is that driving is considered as a cognitively initiated and driven task. Then driving can be viewed from the driver as a task passing through hierarchical levels from cognitive to psychomotor control. With this in mind it is possible to organise the four control levels in ECOM as starting with the top level of control *targeting* as an inner control loop and the *monitoring*, *regulating* and *controlling* loops as concentric circles with increasing diameters (see Figure 14).

Thus, what Hollnagel described as the lowest level of control *controlling* will be the outer circle representing the physical interaction with the interface to the vehicle’s physical controls (e.g. steering wheel, pedals or various driver support systems). Control goals are determined in the inner control loops and applied in the outer control loops. That is to say that e.g. in the *targeting* control loop the goals are determined for the *monitoring* control loop. This flow is represented by the outward-bound arrow labelled *goals* at the top of Figure 14. Feedback used to modify and supervise the control is fed back from outer circles to inner control circles represented by the inward-bound arrow labelled *feedback* at the top of Figure 14. The interaction between the driver and the physical environment is represented by the two arrows labelled *external events* and *actions* at the bottom of Figure 14.
The model described in Figure 14 can be extended by applying a cognitive systems engineering view (Hollnagel, 2002a; Jagacinski & Flach, 2003) in order to consider the total system to be controlled. This means that consecutive control levels will be added outside the control loop representing e.g. support system, vehicle, road, traffic etc. This means that we will have an open system and closed control loops that are connected. All of this will form a hierarchical control structure which can be used to at least understand parts of the relationship between driving task and driver behaviour. How this can be applied will be show with the following example.

7.5.9 Joystick Controlled Cars - an Example

The results from an experiment with joystick controlled cars will be used to exemplify the theoretical discussion above. A manoeuvre test on a closed track was performed with experienced drivers of joystick-controlled cars (Östlund & Peters, 1999). The test included the following three manoeuvres: (1) double-lane change, (2) firm and controlled braking in a narrow curve, and (3) firm and controlled braking on straight road. It was found that time lags in the steering control system caused problems, specifically when performing the double lane-change manoeuvre. Braking in a curve was a manoeuvre, which revealed problems of control interference between steering and braking control. Finally, it was difficult for the test drivers to perform the straight road brake manoeuvre smoothly which was attributed to lack of feedback. The observed problems can be described in terms of cognitive control models like the ECOM.

The time lag problem observed in the double-lane change was handled by the drivers by trying to anticipate the behaviour of the car. The drivers initially had to plan (target) in advance how to move the joystick lever in order to compensate for the time lags and maintain control in the double lane change. It is very difficult to model time lags and a correct guiding model requires a lot of experience and training. It also turned out that
The double lane change manoeuvre was the most difficult task to carry out satisfactory (i.e. without hitting any cones). The joystick drivers performed worse compared to a group of drivers with the same age and driving experience. These drivers drove in a standard car. The joystick drivers hit more cones and produced higher lateral acceleration forces despite driving their own individually adapted cars.

The interference problem observed when braking in a curve mainly affected the activities on the monitoring and regulating levels. The drivers probably had a mental model of how their joysticks worked but it was not sufficient in order to know what direction to move the lever in order to brake without affecting steering control. They had to regulate and monitor their control actions closely in order to adjust the joystick motion. This type of manoeuvre needs to be carried out at least partly as anticipatory control. With increased experience the drivers are likely to develop motor control schemata comparable to the precognitive control proposed by McRue et al. (1977). It was also observed that the drivers compensated performance decrements by driving slowly in the curve. It was difficult for them to maintain the prescribed speed in the experiment.

The lack of tactile feedback when braking on a straight road was something that mainly influenced the activities at the lowest level in the ECOM model or the outer circle in Figure 14, controlling. The drivers were not able to adjust the force applied on the brake lever in order to make a soft stop. It can be speculated that the feedback they experienced, as whole-body g-forces together with the visual cues was not sufficient for the regulation of the brake control function. However, it is probably a delicate task to implement feedback forces to suit the category of drivers who participated in the test e.g. drivers with sever muscular dystrophy. Adaptation companies often claim that these drivers are so extremely weak that they cannot utilize active force feedback. Their force capacity is too low. However, this is probably not true because all manual control depends on some form of force feedback. If it is technically feasible is another issue. In that case it might be possible to investigate other sources of feedback e.g. auditory feedback. However, such feedback will be artificial and not intuitive in the same way as force feedback would probably be.

All of the three identified problems with joystick systems can be described and analysed in terms of time-based safety margins. An adaptation evaluation should determine if safety margins are sufficient under different conditions. Actually, two types of safety margins can be distinguished: subjective and objective. Subjective safety margins could be determined by having the driver drive in real traffic including both self-paced driving and force-paced driving. Subjectively experienced time-pressure, distance and speed control could be used as measures of subjective safety margins. Subjectively determined safety margins are important for the driver’s trust in both the adapted car and his/her own ability to handle the car. The objective safety margin is in a way the ultimate safety limit. Beyond this limit the driver will loose control of the vehicle. Thus, in order to determine the objective safety margins the driver has to be forced to drive close to what is possible or even cross the limit of control. Thus, a closed track manoeuvre test could be included in the adaptation
evaluation. The aim with such a manoeuvre test would not be to set up higher requirements for drivers with disabilities but to ensure that the adaptation will let the driver control the car even in critical situations.

A complete adaptation evaluation should consider driving performance, workload, comfort, trust, and driver acceptance. There are perhaps other aspects that should be considered as well. However, here the focus was on driver’s control of the vehicle which at least is a fundamental adaptation requirement. Thus, it seems like time dependent safety margins is a concept that can be very useful to investigate performance aspects in an adaptation evaluation. Time dependent performance measures as TTC and TLC or the more generic measure Time-to-object (TTO) (van Winsum, 1996) is a way to operationally implement the concept of field of safe travel which can be used to investigate longitudinal and lateral safety margins. TLC is discussed in more detail in a separate chapter.

7.6 Summary

Different driver behaviour models have been discussed in relation different phases of the process from fitness-to-drive assessment to vehicle adaptation evaluation. The first objective of the fitness-to-drive assessment is to discriminate between those capable of driving with or without vehicle adaptation and those who are not. The most appropriate type of driver behaviour models to consider for the medical assessment seems to trait models (e.g. (McKenna, 1982)). Furthermore, the outcome of the medical assessment should serve as an input the prescription phase. Two types of prescriptions should be provided: adaptation and training prescriptions. When prescribing adaptation it seems like taxonomic models like task analysis (McKnight & Adams, 1970b) can provide some help. Even if the most extensive task analysis based driver behaviour model was developed for driver education and training (McKnight & Adams, 1970a) it seems like training prescription can better be done with help of motivational models. However, traditional motivational models (e.g. (Wilde, 1982), (Näätänen & Summala, 1974), and (Fuller, 1984)) do not consider the hierarchical structure of human behaviour. The GDE framework (Hatakka et al., 2002) overcome this limitation by combining hierarchical behaviour models with motivational models. The adaptation evaluation should first of all check if disabilities critical for the driving task have been compensated for. Furthermore, the adaptation evaluation should determine if the driver’s abilities have been used optimally. Human information processing models (e.g. (Wickens, 1992)) can offer some help in this task. However, the adaptation evaluation should also make sure that the driver is provided with an adaptation, which allows driver to drive with sufficient safety margins. Control theory or general systems theory seems to offer a useful framework for driver behaviour models in view of vehicle adaptation. Two important aspects of control are considered in control theory: if the system is open or closed and if the control loop is open or closed. The traditional Stimulus-Response models are based on a closed system but open loop control. This means that the driver and the car are not considered together. Control theory address self-regulating systems and can thus better be used to model adaptive driver behaviour. Simple feedback models can be used to describe closed
loop or compensatory driving behaviour. However, normal driving consists of a combination of anticipatory and compensatory control. This problem was addressed in the servo control model proposed by McRuer and colleagues (1977) which incorporates both feedback and feed forward control. Even if control theory considers the controlled system it does not really explain cognitive mechanisms behind control. This was addressed by e.g. Neisser (1976) and Ashby (1956) who stressed the operators need to understand the system under control i.e. the driver needs to understand or have a functional model of the car and how it is controlled. This was expressed in the “law of requisite variety” (Ashby, 1956). Cognitive Systems Engineering (Hollnagel, 2002a; Jagacinski & Flach, 2003) put control in context and expanded the view of the controlled system. The models discussed so far could however not be operationally translated into control of safety margin. The field of safe travel proposed by Gibson provided a foundation for the concept of safety margins and a guiding mechanism for normal safe driving behaviour. Michon (1985) meant that combining models of vehicle control and perception would constitute a major breakthrough in modelling driver behaviour. Hollnagel (2002b) provided a description of how the control cycle (e.g. the driver’s control of the vehicle) can be understood in terms of time. Finally, Hollnagel (2002a) connected the cognitive control cycle with the hierarchical control models and presented an extended control model (ECOM) which be used to understand and analyse vehicle adaptations. This was exemplified with problems observed in joystick driving.

This discussion of driver behaviour models started out with Michon’s classification of driver behaviour models (Michon, 1985). Reconsidering this classification it seems like different classes of models are more or less suited for different phases in the process from fitness-to-drive to vehicle adaptation (see Table 7). This matching should be regarded as tentative. Digging deeper in to the problem area will most likely reveal a need to consider more than one type of model in order to fully understand different problems or phenomena e.g. even if adaptive control models seems to be well suited for adaptation evaluation they do not consider motivational aspects which probably should be included.

Table 7 Tentative matching of classes of driver behaviour models to the different phases in the process from fitness-to-drive to vehicle adaptation evaluation.

<table>
<thead>
<tr>
<th>Input-Output (Behavioural)</th>
<th>Taxonomic</th>
<th>Functional</th>
</tr>
</thead>
<tbody>
<tr>
<td>Task analyses</td>
<td>Adaptive control models</td>
<td></td>
</tr>
<tr>
<td>(Adaptation Prescription)</td>
<td>(Adaptation Evaluation)</td>
<td></td>
</tr>
<tr>
<td>Internal State (Psychological)</td>
<td>Trait models</td>
<td></td>
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<tr>
<td>(Medical Assessment)</td>
<td>Motivational models</td>
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<td></td>
<td>(Training Prescription)</td>
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</table>
8 Adaptation Evaluation with Focus on Vehicle Control

An outline of what should be included in an adaptation evaluation was presented in chapter 6. This chapter will discuss adaptation evaluation with main focus on vehicle control. This will be done in view of the four experiments that were conducted within the scope of this thesis (paper I, II, IV, VI and VII). It should be kept in mind that the presentation in this chapter is made from a research and development point of view. An operational evaluation should be given a practical form, which makes it possible to carry out the evaluation on the road and a closed track without expensive tools. For a more elaborated discussion concerning practical aspects of adaptation evaluation see Fulland and Peters (1999b).

8.1 General Methodological Considerations

Currently, there are no validated, operational and well-defined criteria for safe driving behaviour that could be used as a reference (French & Hanson, 1998; Ranney & Hunt, 1997; SpriGLE et al., 1995) in order to determine if one adaptation is superior to another. However, criteria aimed to distinguish between safe and unsafe driving behaviour have been proposed by e.g. Brookhuis et al. (2003). Brookhuis and colleagues proposed that such criteria should be specified as both absolute and relative criteria. Absolute criteria define the absolute red line of demarcation for unsafe driver behaviour and relative criteria are defined in relation to individual baseline behaviour. They distinguished three types of criteria: distance to lead car, lateral control, and speed control. However, the proposed criteria have not been validated. This is further discussed in paper VII. The medical requirements in Annex III of the EC directive (EEC, 1991) specify that an adaptation should compensate for the driver’s impairments. This means that the driver should be able to drive equally safe as any other licensed driver. Thus, the most appropriate method for an adaptation evaluation is to conduct comparative investigations. The comparative method could also be used in order to determine which out of several adaptations is superior for an individual driver. Safe driving in this context also means that we have to ensure that the driver does not have to perform at maximum in order to achieve a safe driving behaviour, as this will leave no margins for the driver to cope with critical traffic situations. Furthermore, extensive workload imposed on the driver will affect preventive safety, as there is a risk that fatigue deteriorates driving performance. Finally, capturing the drivers’ opinion concerning the adaptation, driving performance, experienced load etc. will also contribute to the adaptation evaluation in line with the client centred approach advocated in Chapter 6.

8.2 Selection of Test Drivers

As discussed earlier, it is often found that drivers with disabilities are very diverse and constitute a heterogeneous group with respect to their adaptation needs and preferences etc. This can cause problems when trying to develop a generic evaluation method, as there will be too many parameters that has to be controlled. Disabilities caused by Cerebral Palsy (CP) are one category of disabilities, which can be very
diverse and difficult to completely describe with respect to adaptation and training requirements (Falkmer, 2001). Disabilities that are progressive and/or intermittent (e.g. Multiple Sclerosis) can also be very complicated to consider in an adaptation evaluation. On the other hand, disabilities caused by traumatic spinal cord injuries (SCI) are often quite straightforward with respect to the adaptation needs (Peters, 1998). Drivers with SCI have a paresis, which restricts mobility and strength in their limbs and trunk. Of course there can be complicating factors e.g. risk of spastic cramps due to overload, additional disabilities like brain damage etc. Drivers with traumatic SCI are also the most frequent category of drivers with adapted cars. In the survey presented in paper V it was found that almost 30% of the respondents were drivers with SCI (Henriksson & Peters, 2004). Finally, a lot of adaptation experience has been gained for driver with SCI as they were among the first to drive adapted cars (Koppa, 1990). Thus, the majority of subjects who participated in the three simulator experiments included in this dissertation were drivers with traumatic SCI.

8.3 Selection of Evaluation Platform

Both instrumented vehicles and driving simulators can be used to carry out research on adaptation evaluation. In some cases it is also possible to use the driver’s own vehicle. This was done in the manoeuvre test with four way joystick systems which preceded the joystick experiment in the driving simulator (see paper VI) (Östlund & Peters, 1999, 2002). All of these options have their pros and cons (see Table 8).

<table>
<thead>
<tr>
<th>Evaluation platform</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Driving simulator</strong></td>
<td>High controllability, Easy to adapt &amp; simulate functions, Safety critical driving possible, Easy to collect data, High fidelity – high validity</td>
<td>Lack of realism, Difficult to adapt individually, High fidelity – expensive, Low fidelity – low validity</td>
</tr>
<tr>
<td><strong>Instrumented vehicle</strong></td>
<td>Real driving – high realism, High validity, Easy to collect data</td>
<td>Difficult to adapt individually, No safety critical driving possible, Real driving – low controllability</td>
</tr>
<tr>
<td><strong>Own adapted vehicle</strong></td>
<td>Individually adapted, Real driving – high realism, High validity</td>
<td>Difficult to collect data, Low controllability, No safety critical driving possible, Real driving - low controllability</td>
</tr>
</tbody>
</table>

The selection of evaluation platform depends among other things on the severity of the driver’s disability. The more severe disability the more dependent will the driver be that the adaptation is individually fitted. The character of the driving task will also determine if a simulator or a car is most appropriate for the evaluation. The possibilities to adapt the vehicle will also differ between real cars and simulators. In a driving simulator it is possible to test new functions or systems even before they actually exist.
The advanced driving simulator at VTI was used in three of the experiments as it was considered important for the experiments to have a high controllability, to include a safety critical manoeuvres and to simulate advanced driving systems. In addition, using the simulator made the data collection simple and fairly straightforward. It was critical for the validity of the results that the driving simulator was sufficiently advanced to provide a realistic driving situation. Few driving simulators have been subjected to any extensive validation investigation. However, the VTI driving simulator has been validated with good results in a number of experiments (Törnros, Harms, & Alm, 1997). In these experiments it turned out that the moving base system was critical for the external validity. Driving behaviour in the simulator deviated more from driving behaviour on a real road when the moving base was turned off. The motion system was also considered to be important for drivers with SCI. These drivers can be sensitive to acceleration forces as it can affect their stability and thus their ability to control the vehicle. This was also shown in the introductory examples. One disadvantage with the simulator used was that it was rather difficult to enter for drivers using wheelchairs. Summarising, it seems like it can be well worth the high cost associated with the usage of an advanced simulator in research and development projects. The VTI driving simulator is further described in relation to the experiments.

8.4 Evaluated Adaptations

The adaptation equipment evaluated and used in the experiments consisted mainly of adaptations for the primary control of the vehicle, e.g. steering, braking and accelerating. The experiments focused on preventive safety and discomfort during manoeuvre test and general driving in terms of the adaptation evaluation described in section 6.9 (see Table 3). The drivers who participated in the three experiments were all dependent on their upper limbs for the primary control of the car. Technical solutions for hand controlled driving were among the first adaptations for drivers with disabilities that appeared on the market. Hence, a wide range of designs has been developed based on different principles e.g. plain mechanical, electro-mechanical, hydraulic, electro-hydraulic, and electronic. The first types of adaptations for hand controlled braking and accelerating consisted of simple mechanical extension devices operating on the original pedals. Two examples of mechanical adaptations are shown in Figure 15.

The system to the left (Figure 15a) shows two types of acceleration controls (a gas ring, which is pushed to accelerate and a handle placed in front of the steering wheel, which is pulled to accelerate) and a brake handle, which the driver pushes in order to brake. Only one of the acceleration controls will be installed. The system to the right (Figure 15b) consists of a mechanical device with a single handle with which the driver pulls to accelerate and pushes to brake. Most adaptations are designed in a way that the car’s original controls are left unaffected. There are at least two reasons for this: 1. Other members of the family (or anyone else) who is not disabled should as far as possible be able to use the car, 2. The possibility to easy uninstall the adaptation will increase the second hand value of the car.

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When determining what kind of primary control adaptations to be used in the first two experiments it was decided that: 1. it should be adaptations frequently used in Sweden, 2. it should be two systems that were functionally different. The principles for systems selected are shown in Figure 16.

The two hand control systems that were used were different in several aspects. The single lever system (Figure 16 a) was a combined control system with which driver both accelerated (pull) and braked (push). It was installed at the right side of the driver and attached to the floor. The driver could only use one hand for steering with this system. This was expected to influence steering performance. However, the driver did not have to change grip when switching from accelerating to braking. This could have a positive effect on brake reaction time if the time it took to move the lever from acceleration to brake was not too long. The second system consisted of two separate levers mounted on the steering column (Figure 16 b). The driver could have both hands on the steering wheel even when controlling the accelerator. However, there could be a risk that the speed keeping control could interfere with steering control or...
vice versa. With this system the driver was forced to change grip and could only use one hand for steering control while braking. This implementation could affect brake reaction time and perhaps steering performance. In short, it was found that the design of the two systems was different in ways, which could be expected to influence driving performance and workload. Differences in physical workload could emerge from a design, which does allow the driver to distribute the load, force the drive to use the less able limb etc. Workload considerations are also discussed in the presentations of the three experiments.

The same hand controls as in experiment one were used in the second experiment. Furthermore, an ACC (Adaptive Cruise Controller) was installed in the simulator. Apart from the function of a conventional cruise controller the ACC could dynamically adjust speed in order to maintain a safe distance to a lead vehicle. The ACC system is further described in paper II. The ACC was not adapted in any way to drivers with disabilities. However, the function of the ACC was extended so that it included a stop-and-go function. This was done in order to improve the usability of the system for the target group. Much of everyday driving is done in built-up areas where there are a lot of traffic lights. A stop-and-go function would greatly extend the time the driver can have the ACC activated.

Electronic four-way joystick systems are not very common in Sweden. There are only approximately 20 cars equipped with such systems. However, this type of vehicle control technology can be very useful but it is still a need for further development as shown in section 7.5.9 and papers IV, VI and VII. Thus, in the third experiment two alternative joystick designs were investigated. The two systems differed in the way steering and speed/brake was controlled. Two physical joystick designs were used to realise two types of coupling between lateral and longitudinal control. Both systems were based on a conventional four-way joystick system as the central unit (see Figure 17).

![Figure 17 The two joystick systems used in the third experiment. Arrows indicate how steering, accelerating and braking commands.](image)

The first design consisted of a conventional joystick equipped with a fork like grip (see Figure 17 a) specifically developed for drivers with tetraplegia. Steering, accelerating
and braking were controlled with radial motions of the grip in lateral respectively longitudinal directions. The other joystick design was implemented by attaching a mechanical device that transformed the radial speed controlling motion into a linear longitudinal motion. Thus, the driver controlled speed by moving his/her arm back and forth while steering was controlled with radial motions around an axis through the arm (See Figure 17 b). The driver’s hand was placed in a tri-pin grip that could be adjusted to fit different arms and hands.

Two types of feedback (active and passive) in the joystick were also investigated apart from the different physical designs of the two joystick systems. Thus, actually four different types of joystick control systems for steering, accelerating and braking were evaluated in the third experiment. The evaluation focused on preventive safety in terms of time based safety margins, workload and driver opinion.

It was not possible to make the adaptations in the driving simulator as complete as in the participants’ own vehicles. However, experienced driving instructors and vehicle adaptation experts were consulted in order to ensure that the adaptations should be sufficient for drivers who participated. One critical aspect that was considered with care was to ensure that the drivers were seated sufficiently stable.

8.5 The Driving Task
The driving task used in an adaptation evaluation has to be designed in correspondence with the evaluation objectives. If for example physical workload can be expected to be a limiting factor it will be important to include both prolonged driving (static load) and advanced manoeuvres requiring strength, reaction, endurance, co-ordination etc. (dynamic load). The driving task should also be as realistic as possible in order to convince the drivers to drive as they usually do. The drivers who participated in the experiments were instructed to drive, as they would do under the same conditions in their own cars. However, for the manoeuvre tests they were given specific instructions.

Workload and performance were prioritised in the first experiment. Overload was expected to be a problem. Insufficient adaptation could affect the driver’s performance (reaction time). Thus, the driving distance was quite long (80 km). The route was divided into two equal sections in order to detect possible performance and behaviour degradations as signs of physical fatigue. Both an artificial choice reaction task and an evasive manoeuvre were included in order to measure performance. This is further discussed in paper I.

The objective in the second experiment was to evaluate the potential gain from a specific adaptation aiming at alleviating the physical load on the driver. The driving task was designed in accordance with this objective and included a several situations, which allowed the driver to use all ACC functions. The driving task was extended to 100 km compared to the first experiment. This was done in order to make the load on the driver even more pronounced and thus make it possible to detect physical fatigue. However, the distance was not unrealistically long, just half the distance between
Linköping and Stockholm. The same brake reaction task as in the first experiment was included. Details about the driving tasks can be found in paper II.

The driving task in the third experiment consisted of 20 km long rural road driving and three double lane change manoeuvres. The driving task was repeated three times for each of the four joystick designs. However, the first drive for each condition was considered a training drive and not included in the analysis. The two succeeding drives were used in the analysis and the repetition of driving task was motivated by the objective to study learning effects. The driving task was designed to include both simple and more demanding situations. Driving on rural road was considered to be simple but it should also reveal the driver’s ability to control the car with sufficient safety margins at normal driving conditions. Particularly, lateral control was of interest. Two car-following situations were included in order to study the driver’s longitudinal control. The lane change manoeuvre was considered to be more demanding compared to driving on the road. Thus, the manoeuvre test was more devoted to measure performance while rural road driving was considered to measure normal driving behaviour.

8.6 Measures
The measures used in the three experiments were selected in accordance with the research questions and with the objective to analyse relevant dependent variables. The measures that were used can be grouped as driver behaviour and performance, workload, adaptation usage and driver opinion. Both objective and subjective measures were used. Most of the measures were inherited from a long experience of driving simulator experiments conducted by many researchers. Some measures were developed for the specific purpose of evaluating vehicle adaptations specifically with focus on safety margins. In most cases individual and group means were calculated and analysis of variance (ANOVA) was used to analyse the data. A significance level of 5% was used in most statistical tests.

8.6.1 Driver Performance and Behaviour
Several different measures were used to analyse driver performance and behaviour. Different approaches were used to measure the driver’s safety margins in accordance with the discussion in Chapter 7. First of all, in order to measure driver performance according to Evan’s definition, i.e. “what the driver can do” (Evans, 1991), the driving task could be made difficult or a reaction time task could be used. A brake reaction time task was used in the experiments presented in paper I and II. However, in the joystick evaluation, paper IV, VI and VII, was a manoeuvre test used. The manoeuvre test was used to investigate if the adaptation would allow the driver to perform sufficiently to manage a critical situation.

8.6.1.1 Lateral Control
The driver behaviour measures used can be divided into measures of lateral and longitudinal control. Mean lateral position and SDLP (standard deviation of lateral
position) were used to analyse lateral control in the first two experiments. However, it was found that this was not sufficient as it did not give information about the safety margins (Peters, 2001c). Thus, the conclusion was to investigate the TLC (Time-to-line-crossing) measure in the joystick experiment. This was in line with the concept of safety margins as discussed in chapter 7.

The TLC measure was developed by Godthelp, Milgram, & Blaauw (1984) in order to analyse the driver’s lateral control strategy. Their interest was to specifically study anticipatory driving behaviour. Godthelp and his colleagues (Godthelp, 1986; Godthelp et al., 1984) conducted two experiments in which an open loop (anticipatory) driving strategy was enforced on the drivers by use of a visual occlusion mechanism. The drivers were blinded but could unveil the occlusion when they thought they needed more visual information for a short duration but the eyes were soon after occluded again. The assumption was that driving to a large extent is a task that is carried out on the basis of visual perception.

TLC was defined as the time left until a moving vehicle crosses either side of the lane boundaries (white lines) under the assumption that the vehicle continues along the same travel path (i.e. constant heading angle) maintaining the current momentary motion (i.e. speed). As long as the driver follows the road curvature perfectly TLC will be indefinite – the driver will never cross the lane boundaries (white lines). However, perfect lateral control is not possible more than for short time periods due to changing road curvature and elevation, road texture, wind, vehicle instability, driver instability etc. Normal steering control can be described a pendulum-like motion moving back and forth toward either of the lane boundaries. The driver makes a steering correction when coming too close to e.g. one of the white lines defining the lane boundaries and then the vehicle will start moving away from one line towards the other. TLC will reach a minimum approximately when the driver makes a steering correction to move away from the line. TLC minimum and the distribution of successive TLC minima can be used as a measure of the lateral safety margin. Thus, TLC seems to be a good cue to determine a driver’s lateral control which also considers speed as it is a time based measure.

TLC can be calculated at each moment on the basis of lateral lane position, heading angle, vehicle speed and commanded steering angle (Godthelp et al., 1984). However, there are two major problems associated with TLC as it was proposed by Godthelp: 1. real time calculation is complex and require sensor data with high resolution and precision, 2. TLC is computed differently on straight road segments compared to curved segments (van Winsum, Brookhuis, & de Waard, 1998). TLC is in general terms calculated as:

\[
TLC = \frac{DLC}{u},
\]

with \(DLC\) = Distance to Line Crossing along the vehicle path and \(u\) = speed of the car along the path.
Thus, a simple approximation of TLC would be to just divide lateral position and lateral speed. However, Van Winsum, Brookhuis and de Waard (van Winsum, Brookhuis, & de Waard, 2000) found that this approximating of TLC was not sufficiently accurate. However, if the change in lateral velocity was included this new approximation resembles accurate TLC in terms of values of minima and temporal characteristics.

\[ \text{TLC}_{\text{approx}} = \frac{\text{Lateral position}}{\text{Lateral speed} + \text{Lateral speed change}} \]

This second approximation was used to calculate TLC in the joystick experiment (paper IV and VII). Using this approximation will make it much easier to get TLC data as only lateral position data is required. However, lateral position data should have sufficient resolution (2 cm or better) and be recorded with sufficient frequency (10 Hz or better).

In order to determine the TLC based safety margins relevant TLC minima have to be identified. Occasionally, some TLC minima can be invalid or irrelevant e.g. local TLC minima caused by vehicle instability. The TLC minima that should be considered are those which actually describe the driver’s steering control. The following criteria were used to identify valid TLC minima:

1) The TLC wave duration (time from start of movement to left (or right) to end of left (or right) should be at least 1 second. This is a rule of thumb and can be change to other values but not too short. Short lasting TLC minima waves are most likely caused by vehicle instability and not caused by driver steering control actions.

2) A TLC minimum of over 15 seconds does not mean anything in terms of safety margins. Such high TLC values mean that the driver is virtually following the road curvature perfectly. Thus, only TLC minima under 15 second have been considered.

Once the relevant TLC minima were identified the following derived measures were calculated and used in the analysis.

- \( \text{Min TLC}_{\text{min}} \) (Shortest TLC minima)
- \( \text{Mean TLC}_{\text{min}} \)
- \( \text{Number of TLC}_{\text{min}} \) below 1 second (during a certain distance or time)

A final aspect of TCL as a safety margin measure is to determine the relevant lines that should be used to calculate TLC. The TLC concept is based on the assumption that the driver steers in order to keep the car within the lane boundaries (white lines). This is likely to be true if we exclude situations like e.g. overtaking and curve cutting. But if e.g. there is a wide hard shoulder and oncoming traffic it might be that the driver prefers to drive more to right in order to maintain equal safety margins both to the right and the left side. In this case it seems more like the driver is steering according to
some imaginary lane boundaries. In other words the driver behaviour can be described in the terms of subjective field of safe travel (Gibson & Crooks, 1938). Oncoming traffic will encroach upon the driver’s field of safe travel and it is likely that the driver will change the heading direction to compensate and maintain a wide as possible field of safe travel. Thus, it might be needed to find the virtual travel path boundaries used by the drive in order to correctly calculate and analyse TLC. This is further discussed in paper VII.

8.6.1.2 Longitudinal Control
Mean speed and standard deviation of speed was used as rough measures of the driver’s longitudinal control. However, this did not tell much about the longitudinal safety margins. Thus, min headway distance was used to determine how close a driver actually came to the lead vehicle and the risk of rear-end collision. However, this measure does not actually tell enough about the longitudinal safety margin, as e.g. speed is not considered. Driving close at high speed is far more dangerous compared to low speed. TTC (Time-To-Collision) and TH (Time Headway) can be used as a time based measure of longitudinal safety margin (van der Hulst, 1999; van Winsum, 1996). Min TH, min TTC and mean TTC were used to evaluate the drive’s longitudinal safety margin when there was other lead traffic that the driver had to interact with.

8.6.1.3 Combined Lateral and Longitudinal Control in Joystick Driving
Verwey (1994) listed some issues (see also section 6.9) that should be considered in an adaptation evaluation of particular interest for joystick driving:

- the risk of interference between control tasks e.g. lateral and longitudinal control
- super light controls (like joysticks) can require continuous corrections which could be very tiring
- control-by-wire controls may suppress relevant feedback to the driver

Thus, in order to evaluate the tested joystick systems a more detailed analysis was done with respect to how the driver moved the joystick to control the car. The lateral and longitudinal angles of the joystick were used to calculate measures that could be used to detect possible lack of control and occurrence of interference between lateral and longitudinal control:

- **Joystick lateral reversal rate**, defined as the total number of times the direction of joystick movements was turned per kilometre. This was a measure of how frequently the driver moved the joystick in order to maintain control. Increased frequent small joystick motions can be tiring for driver and sign of degrading control.

- **Correlation between lateral & longitudinal joystick speed**, calculated for each double lane change as the correlation between the absolute values of the lateral and longitudinal joystick angular speed. This was a measure that would
increase when longitudinal and lateral joystick angle are changed simultaneously. This was a measure used as an indicator of interference between lateral and longitudinal control.

For a further discussion about the measures used to evaluate the joystick control systems see paper VII.

8.6.2 Workload

Workload can be split into mental and physical workload. High mental workload will increase the risk of driver control failures and road accidents. Thus, mental workload assessment is a concern specifically in view of possible negative effects due to the introduction of new technology like ITS in cars (de Waard, 1996). De Waard (1996) presented a comprehensive overview of how driver mental workload can be measured and analyzed. The physical workload on the driver is usually not thought of as a problem for the average driver. However, physical workload is a major concern for drivers with disabilities and it is critical that the adaptation is done in way that the physical workload in minimised. Thus, both physical and mental workload should be addressed in an adaptation evaluation.

There are in principle four different ways to measure workload: primary task performance, secondary task performance, subjective rating scales, and physiological measures (Wickens, 1992). Primary task performance was more or less used to analyse the driver’s workload in all three experiments. A choice reaction time task was used as a secondary task performance test was used in the first two experiments (Paper I and II).

Subjective rating scales were used in all three experiments. The NASA – RTLX (NASA – Raw Task Load Index) was used to capture subjective workload (Byers, Bittner, & Hill, 1989; Hart & Staveland, 1988) in the two first experiments (Paper I and II). The NASA – RTLX measures six workload factors: mental demand, physical demand, time pressure, performance, effort and frustration using a continuous scale ranging from very low to very high (0 - 100). This tool has been used to measure workload for a broad variety of tasks but it was developed to measure workload on military pilots. It is fairly simple to administrate and analyze. However, it cannot be used to measure dynamic changes in workload. The NASA-RTLX was used to measure subjective workload for different subtasks, e.g. car following, in the second experiment (Peters, 2001a). A simplified workload rating scale was used in the third experiment (Paper IV and VII). It was not considered necessary to measure all six workload factors of the NASA – RTLX but still essential to distinguish between mental and physical workload. A one-dimensional scale like the OW (Overall Workload) was not considered appropriate (Hill et al., 1992). Thus, the drivers rated the combined mental and physical load and each factor separately on a 7-styped semantic differential scale ranging from very low to very high in the third experiment.

Physiological measures are more suited to investigate dynamic changes in workload. Physiological measures were not considered essential in the first two experiments.
However, difference in max force in the arm used to control the accelerator and brake before and after the drive was used to assess effects of physical fatigue in the first experiment (Paper I). In the third experiment were physiological measures of both mental and physical workload used. Thus, EMG (electromyogram) was used to measure muscular load on the driver’s upper arm and shoulder (Birch, Juul-Kristensen, Jensen, Finsen, & Christensen, 2000). Furthermore, ECG (electrocardiogram) was used to calculate HRV (heart rate variability) as a physiological measure of mental workload (Kalsbeek & Ettema, 1963; Mulder, 1988; Wilson, 1992).

8.6.3 Usage of Driver Support System

In the second experiment (Paper II) it was considered important to analyse the usage of the ACC system as this was expected to give a measure of how useful the driver considered the ACC to be. When the ACC was in use the driver was free to use the right hand for steering and reduce the load on the left hand. The driver’s behaviour was recorded and analysed.

8.6.4 Drivers’ Opinion

The drivers’ opinions were recorded with use of different questionnaires in all three experiments. Answers were often given on semantic differential scales with 7 steps but other alternatives ranging from dichotomous alternative to free spoken comments were also used. The drivers have lots information that can be vital to capture in an adaptation evaluation as pointed out in chapter 6. A client can be a very sensitive probe instrument but it can also be an instrument which can be difficult to use and understand. Thus, designing questionnaires is an art that should be treated seriously. Questions should be phrased simple and concrete and the answer alternatives should be easily understandable both for the respondent and for the person doing the analysis of the results. One often neglected part is to provide the right instructions and to train the respondent to use e.g. rating scales for workload assessment. However, questionnaires were not a major concern for this thesis and the approach applied in all three experiments was rather conservative. Thus, the use of questionnaires was rather limited even if some questionnaires were used repeatedly e.g. performance and workload questionnaires in experiment two and three.

8.7 Summary

Comparative tests seem to be appropriate in order to determine if an adaptation compensates for a driver’s disabilities and which adaptation is most appropriate for a driver or a group of drivers. Choosing a group of driver for whom it was possible to make some general conclusion turned out to be difficult and the most appropriate group found was drivers with SCI. The advanced driving simulator was considered the best experimental platform for all experiments except the first manoeuvre test. An instrumented vehicle with the possibility to install different adaptations would have been an interesting complement to the simulator. Some adaptation companies use such cars and the Veterans Administration in the US has developed a van that is used for driver assessment. Two criteria were used to select the adaptive equipment used in the experiments. The first was to evaluate some commonly used adaptations for primary
control, with some functional differences, i.e. the hand control used in the first and second experiment. The second criterion was to choose a very advanced adaptation with some known problems but with a high potential, i.e. the four-way joystick control system. The driving task was designed to disclose potential problems with the tested adaptations. Measures used in the experiments evolved during the course of the tests. Different measures of lateral and longitudinal control were prioritised as much of the focus was on the driver’s primary control of the vehicle. However, a number of other measures were also used e.g. physiological and subjective rating measures.
9 Summary of experimental results

A summary of the results from the three experiments carried out within the scope of this thesis is presented in this chapter.

9.1 Experiment 1 Driving Performance and Workload Assessment of Drivers with Tetraplegia - an Adaptation Evaluation Framework

This experiment is described in paper I. The purpose of the first driving simulator experiment was to establish a baseline for further research on vehicle adaptation evaluation for drivers with physical disabilities. The objective was more specifically, to evaluate some common adaptations with respect to how well they compensated for the drivers' disabilities. A group of twenty-six experienced drivers with SCI (tetraplegia) were compared to a group of equal size with able-bodied drivers. The two groups were matched in terms of age, gender and driving experience in order to minimise irrelevant variations between the groups. Furthermore, the drivers with SCI were divided in two subgroups depending on which of two types of hand-operated controls for accelerating and braking they used in their cars. The two subtypes tested were: 1 a floor mounted combined hand control and 2. a dual lever system mounted on the steering column. Both hand controls were operated with the right hand. The participants drove with the same type of control in the simulator as they had installed in their own cars. The two experimental subgroups consisted of thirteen drivers each. The control group consisted of an equal number of able-bodied drivers who used standard pedals for accelerating and braking. This was in accordance with the comparative evaluation approach described in chapter 8. The driving task, 80 km rural road driving, was not very demanding with regard to manoeuvring the vehicle, even if the task included an evasive manoeuvre in order to avoid crashing in to a parked car. The manoeuvre test used in the third experiment with joysticks was far more demanding and was furthermore repeated several times. The results showed that the drivers with SCI and the control group had similar driving behaviour with respect to speed, speed variation and lateral lane position. This could be interpreted as if adaptation more or less filled its purpose. However, the experimental group had a slightly but significantly longer brake reaction time (10%) to unexpected events. This result deviated from what Richter & Hyman (1974) found but conformed to other findings (Sprigle et al., 1995). Workload assessment revealed that drivers with tetraplegia experienced a significantly greater time pressure and spent more effort than did the able-bodied drivers to perform the way they did. They were also physically more tired from braking and accelerating. However, the method used to detect physical fatigue in the right arm, which was used to operate the hand control, did not reveal any signs of degraded force capacity. The drivers with tetraplegia using separate levers mounted on the steering column had a greater SDLP (standard deviation in lateral lane position), 7 cm. It was suggested that the SDLP difference could be caused by interference between speed and steering control. The drivers using the floor mounted combined lever were more tired from braking and accelerating. Insufficient arm support could have contributed to make it more tiring to use this system. The observed differences suggested that the adaptation was not satisfactory. Higher workload could be caused
by insufficient individual adaptation in the simulator but also due to more general design problems of hand controls. From surveys it has been reported that drivers of adapted car experience driving as physically loading (Nicolle et al., 1992). In view of the next experiment it was suggested that the higher physical load could be alleviated by support systems, e.g. Adaptive Cruise Controller (ACC). It was later also found that 95 percent of participating drivers in the second experiment had a conventional cruise controlled in their own cars.

9.2 Experiment 2 Adaptation Evaluation – An Adaptive Cruise Control (ACC) system used by Drivers with Lower Limb Disabilities

This experiment is described in paper II. Twenty subjects with lower limb disabilities participated in the second simulator experiment. All drivers were used to drive with hand controls for accelerating and braking. The purpose of the experiment was to investigate how an Adaptive Cruise Control (ACC) system together with two different hand controls for accelerator and brake influenced workload, comfort and driving behaviour and to further develop a method to evaluate vehicle adaptations for drivers with disabilities. The ACC system could maintain a constant speed selected and set by the driver. Furthermore, the ACC adapted the speed in order to keep a safe distance to a leading vehicle. A stop-and-go function was also integrated in the ACC system. The stop-and-go function made the car stop at e.g. a traffic sign if a lead vehicle stopped. When the car in front started to drive the ACC would accelerate the car to reach the set speed without any driver action required. The same types of hand controls for accelerating and braking as in experiment one were used in this experiment. The hand controls were different both with respect to design, combined or separate levers, and position, on the steering column or between the front seats. All subjects drove 100 km at two occasions, with and without the ACC system available but with the same hand controls at both occasions. Subjective workload was found to be significantly lower and performance better for the ACC condition. The difference in speed variation between manual and ACC supported driving increased with the distance driven which conforms to found difference in workload. The subjects thought they could control both speed and distance to lead vehicles better with the ACC available. ACC driving did not significantly influence reaction time, speed level, lateral position or variation in lateral position. Headway during car following situations was shorter for the ACC condition compared to manual driving. This result was interpreted as ACC used a too short headway for this group of drivers. Especially, when considering that the reversed result was obtained for able-bodied drivers using the same ACC system (Nilsson & Näbo, 1995). The results indicated that that headway should be individually adjustable according to driver’s characteristics and preferences within a certain range. The need of adjustable headway is likely to be even more pronounced in bad weather conditions, night time driving etc. The need for ITS guidelines was also addressed paper III (Nicolle & Peters, 1999). The ACC system was well received, trusted, and wanted. It was concluded that the ACC system substantially decreased workload, increased comfort and did not influence safety negatively. However, the user interface of the ACC did not seem to be optimal with respect to the needs of the participants even if this was only tentatively included in the evaluation. The only difference found
between the two types of hand controls was that drivers using the dual lever system had less variation in lateral position. It was concluded that the evaluation method used proved to be useful but further development was needed.

9.3 Experiment 3: Joystick controlled driving for drivers with physical disabilities – a driving simulator experiment

The third experiment, described in paper IV and VII, was preceded by a manoeuvre test on a closed track with experienced drivers of joystick cars, described in paper VI. The findings from the manoeuvre test were used to formulate hypothesis for the third experiment. The experiment was conducted with the objective to investigate two salient design features of four-way joystick systems for driving a car. The features tested were the degree of coupling between lateral and longitudinal control and passive/active feedback. The joystick was aimed to be used in a passenger car for steering, braking, and accelerating by drivers with severe disabilities. Presently available joystick systems are hard to learn and difficult to use (Strano, 1997; Östlund, 1999). The initial manoeuvre test revealed that the observed problems emerged from interference between lateral and longitudinal control, lack of feedback, and time lags (Östlund & Peters, 1999). The behaviour of the car is difficult to predict for the driver when driving with such a joystick. Four different joystick designs were developed and tested by combining two factors: coupled/decoupled control and active/passive feedback. Time lags were made similar to what is found in conventional controls (steering wheel and pedals) in standard cars. It was expected that decoupling and active feedback would provide better control, less workload and make it easier to learn how to drive with a joystick. Sixteen experienced drivers with spinal cord injuries at cervical level participated in the experiment. The drivers were all paralysed in their legs and they used their upper limbs to drive their cars. They were all inexperienced with joystick driving. For practical reasons it was not possible to use experienced joystick drivers. The driving task consisted of both driving on a rural road and a double lane change manoeuvre. All subjects drove with all four joystick systems. Cognitive Systems Engineering (Hollnagel, 2002a; Jagacinski & Flach, 2003) was used to argue for time based safety margin measures as a tool to determine which design was superior but also as a mean to understand the observed problems. Even if the participants were diagnostically homogenous it turned out that they were functionally diverse which contributed to a large variation in data. Thus, the analysis was done both for the total group and for two separate groups of equal size depending on their arm and hand function. It was found that decoupling of lateral and longitudinal control at least partly provided better control and less workload. This was specifically true for drivers with better hand and arm motor function. Active feedback was experienced as positive together with the decoupled control by the same group of drivers and provided them with better control during the lane change manoeuvre. However, the drivers with less arm and hand function were more in favour of passive feedback and it seemed like the active feedback forces were even disturbing to them. The reduction of time lags contributed to make it easy to learn to drive with the tested joysticks but active feedback and decoupling did not seem to facilitate learning. It was concluded that reduced time lags, uncoupled lateral and longitudinal control motions
and active feedback have a potential to improve control and facilitate driving with a four-way joystick but the adaptation needs to be individually adjusted. It was concluded that a manoeuvre test should be included in an adaptation evaluation as it was considered to have a good potential to disclose insufficient adaptation. Unfortunately, one of the planned manoeuvres, brake in a curve, could not be used due to risk of nausea. This problem could be due to limitations in the moving base system or vehicle model of the used simulator. Finally, it seemed like the proposed measures of time based safety margins were not very useful in detecting difference between the tested designs.

9.4 Summary
The conducted experiments provided a lot of useful knowledge about drivers with physical disabilities and vehicle adaptations. Workload which can be a problem and limiting the mobility can be reduced by improved adaptations. ITS certainly has a potential to provide better adaptations but drivers with disabilities might require extended possibilities to adapt these systems individually. However, this group of drivers should be considered when designing ITS system in order to reduce the needs for postproduction adaptation. Joystick controlled driving is an alternative for drivers with severe disabilities. The technology opens for more individually adapted interfaces between the driver and the vehicle. Small residual abilities can be used for driving. However, current joystick systems are not perfect and there seems to be a potential for improvements. Manoeuvre tests seem to be highly relevant as one among other methods to evaluate vehicle adaptations. How such manoeuvre tests should be designed in detail requires more research and knowledge but those used to study the joysticks can be used as a start. The last experiment in the simulator highlighted some problems with simulator driving. Some driver groups were excluded and some manoeuvres seemed difficult to implement. Thus, adaptable instrumented vehicles and closed track driving could be an alternative for further research.
10 Discussion, conclusions and further work

10.1 Relevance

It might appear as if this thesis addresses a minor problem. First of all, the value of independent mobility cannot be overestimated in line with what was said in the prologue. Independent mobility contributes to improve quality of life. The need for mobility is also recognised by the society as it is specifically stated that people with disabilities should have access to the transport resources. It can be argued that the number of drivers with adapted cars constitutes just a tiny fraction of the total driving population. However, the proportion of travellers with disabilities is constantly growing and thus, the number of drivers of adapted cars. Furthermore, if these drivers are not considered there will be a faster increase of drivers who are made handicapped by modern car design. Finally, understanding the problems drivers with disabilities face can provide a possibility to discover badly designed environments for all. Bad designs can be obscured during normal use by human adaptability but can be fatal in a critical situation. Thus, the addressed problem is not trifling even in quantitative terms.

10.2 Discussion and conclusions in relation to the objectives

Three objectives were formulated for this thesis:

1. Describe the process for assessing and licensing drivers with physical disabilities and approval of adapted cars in Sweden.
2. Identify pros and cons in the current process and relevant regulations.
3. Develop a framework for evaluating vehicle adaptations aimed to compensate for physical disabilities.

The first two objectives were addressed in chapter 5. Furthermore, this topic was extensively dealt with in a couple of reports (Fulland & Peters, 1999b; Peters & Östlund, 1999a, 1999b). The principles for assessing drivers with physical disabilities and adapting cars were also discussed in detail in chapter 6. Concerning the situation in Sweden there is a potential for improvements as summarised in chapter 5. The work included in this thesis provides ample material for decisions and actions. Subsequently, the first two objectives should be fulfilled. The third objective will be discussed and commented in relation to each chapter. The first two introductory chapters are left without comments.

Chapter 3 highlighted the problem of determining the size of the target population. However, the coding system for conditioned driving licenses will in a few years make it possible to identify and describe the group of drivers with adapted cars. It will also be possible to identify adaptation requirements. However, a corresponding coding system of adapted car should be introduced. When such a system has been implemented there will be no need for individual exemptions. The driver can drive any car with the right adaptation installed. The current situation does not provide any benefit to the driver. The application of the system in Sweden is far from perfect.
There are drivers with unconditioned licenses who drive adapted cars. There are also problems with incorrectly registered vehicles. How these problems should be solved is unclear but something should be done. Finally, it would be interesting to learn how the police act when they stop a driver with a conditioned driving licence.

The knowledge about traffic safety and adapted cars was addressed in chapter 4. It is obvious that the knowledge is very limited and there is a need for further investigations. It seems rather likely that drivers of adapted cars in general are not at greater risk compared to drivers in general. However, the knowledge of why and what type of accidents and incidents these drivers are involved in is very limited. For instance, to what extent do malfunctioning adaptations cause accidents? To what extent is the protective safety affected by installations of adaptations (e.g. deactivation of airbags)? Even more interesting would be to identify drivers who gave up driving or failed to get a driving license and investigate to what extent the adaptation was a problem. Anyhow, there seems to be no reason to be more restrictive in licensing drivers with physical disabilities.

What was included in chapter 6 could be used as a stating point for compiling a training course for driving assessors. There are some instructive publications like the example from Louisiana Tech included in chapter 6 but not many. There are very few courses for driving assessors. An exception is the assessment centre MAVIS/DfT in the UK, who gives a training course. It could be a worthwhile to learn from their experience in view of developing a similar training scheme in Sweden for traffic inspectors and occupational therapists. The system applied in the UK cannot be transferred directly to Sweden but the assessment of fitness to drive should not deviate substantially. Specifically considering that it is the European driving licence directive that applies in both countries. Furthermore, the IST project CONSENSUS where Sweden participates aims to contribute to a harmonised assessment of drivers with disabilities and to establish a minimum standard across Europe (Peters et al., 2004). Guidelines on how to assess drivers with different diagnoses are compiled within this project which could be of value to harmonise the assessment of fitness to drive. The behind the wheel assessment should be further developed in relations to different disabilities and also standardised. Finally, the adaptation should be thoroughly tested with the driver before the cars is handed over to the driver. The outlined adaptation evaluation (Peters et al., 2000) should be considered as an idea which needs to be tested and further developed.

Chapter 7 provided a theoretical view of how driving can be modelled in view of drivers with adapted cars. The most essential part of this chapter was the description of how problems related to insufficient adaptation can be understood and analysed. CSE can be used as a framework to analyse driving with a system perspective (from basic control to goals for life), to connect abilities used by the driver (interdependencies between different abilities) and to consider time requirements (speed and control loop time). The applicability of CSE was exemplified with an analysis of observed problems with joystick driving. The CSE could also be used to develop ideas of how to compensate for missing abilities. CSE seems to be holistic model in view of driving.
Even so, it could be difficult to consider the influence of the driver’s intentions and priorities on the control loop. The underlying assumption of CSE and control theory is that the driver’s objective is to decrease system entropy (or uncertainty) (Wiener, 1954). Sometime this is not the case, e.g. consider the fundamental regulator paradox (Weinberg & Weinberg, 1979). It might be that the driver on purpose gets out of control in order to gain control on a higher level. What strategy the driver uses can be obscured for the experimenter or assessor. Thus, it can be difficult to interpret the driver’s behaviour as the intentions might not be known. It is of course reasonable to assume that being in control is the overall objective. However, at higher levels of the control hierarchy it seems like driver behaviour becomes more diverse. The cognitive influence on the control increases at higher levels. Thus, one approach would be to measure and assess basic (reactive) control behaviour in order to limit the individual differences. Even so, it would be difficult to know for sure how well reactive behaviour will reflect the driver’s control.

Chapter 8 focused on the transfer from theory to experimental methods and identification of relevant measures. Initially, the research question has to be formulated. A relevant target group and adaptation should be defined. The ambition throughout the experiments conducted was to provide some answers that were applicable to at least one category of drivers. However, this turned out to be difficult due to individual diversity. In conclusion, it seems like case studies could be an alternative for further research. This implies that more effort should be devoted to test individual adaptations. This will also have consequences for the selection of evaluation platform. Instrumented vehicles could be a better suited platform than simulators for case studies. Furthermore, an instrumented vehicle could solve some problems with driving simulators, e.g. more freedom to designing the manoeuvre test. On the other hand there could be disadvantages with instrumented vehicles when choosing the adaptation to be tested e.g. the joystick experiment would have been difficult and more expensive to realise with an instrumented vehicle. Designing the driving task can be tricky but the manoeuvre tests that were used seemed to be sufficiently demanding. Thus, it was proposed that similar manoeuvre tests should be mandatory in an adaptation evaluation.

Eventually, relevant measures for the experiment should be determined. Relevant means that e.g. the results should be possible to interpret. Time based safety margins seem to be relevant for evaluating adaptations as it can be a measure of driver’s room for anticipation. However, there are some problems with how to interpret possible results. This will be exemplified with some remarks about TLC. The interpretation of TLC data as a measure of safety margins is not straight away easy. There are several ways to interpret TLC data. Either as a stand-alone value compared to a criteria (e.g. TCL under 1 second is unsafe), or in combinations with other measures (e.g. a mean \( \text{TLC}_{\text{min}} \) under 1 second together with increased SDLP, driving close to the lane boundaries during several seconds is unsafe). Combining measures and corresponding criteria can hopefully be used to better determine if the behaviour is safe or not. The objective is to assess the adaptation. However, differences in TLC data could be a result of the adaptation or intended driving behaviour. The adaptation could be such
that it did not allow the driver to drive with sufficient safety margins even if that was the driver’s intention. In this case a higher TLC$_{\text{min}}$ value for one adaptation compared to another could be interpreted as favourable. On the other hand, the adaptation could be such that the driver had very good control of the car and did not have to drive with large safety margins. In this case a higher TLC$_{\text{min}}$ value for one adaptation compared to another would not necessary be favourable. Finally, it is not always clear what the driver uses as guiding reference for steering control. Crossing the lane boundaries can be an alternative specifically if there is a wide hard shoulder. In conclusion, TLC is probably a relevant measure of lateral safety margin but it should not be considered in isolation and the analysis of TLC data should be done with great care.

The problem of knowing the driver’s intentions was touched upon above. There is probably no easy way to definitely solve this dilemma but there are some possibilities. Measuring basic reactions can be one way. This was applied when developing and using measures describing how the drivers moved the joystick. This approach was based on the assumptions that the driver’s intention was to be in control and thus aiming to decrease system entropy. Another approach could be to use subjective measures to get some insight of the driver’s intentions possibly also in combination with physiological measures. Anyhow, there certainly is a need for further research on what measures to use and how to conduct adaptation evaluations. The experiments that were conducted gave some insight to the problem of how to adapt and evaluate adaptations for drivers with physical disabilities. Furthermore it provides a framework according to the third objective. However, now is the time to move from the laboratory research to do some research in the wild - real life (Hutchins, 1995)!

10.3 A vision for the future

Finally, I will give my vision of the future. Without visions there is no guidance of what to strive for. Here is mine, what is yours? The handbook on how to choose car and adaptation, produced together with SNRA, is well received with a lot of feedback for improvements. VTI gets money to print the handbook. The vehicle grant system is transferred to SNRA and the peculiar limitations are eliminated. Those who are entitled to the grants get it without delay. What is required to compensate for the disabilities is covered by the grant. VTI is engaged to contribute to developing training courses, setting up and evaluating assessment centres. There are some assessment centres where traffic inspectors and occupational therapists collaborate in the fitness to drive assessment and vehicle adaptation evaluation. Additional expertise is available on demand. A mandatory adaptation evaluation is introduced as a support and quality assurance for drivers of adapted cars. Adaptation companies are certified. Adaptations are included in the whole vehicle approval. The vehicle inspection has implemented new routines which include testing of the adaptation. The idea with the driving licence coding system has been complemented with a coding system of adapted cars and need for individual exemptions are eliminated. The driver can use any car with a coding which corresponds to the conditions on the license. Eventually drivers with disabilities are recognised by car manufacturers of important customers and they have an
influence on the design of the cars which will facilitate the individual fitting of the car. Finally, I wish I can contribute to realise this vision. Dimídiwin facti qui coepit habet?
11 Acknowledgements

There are so many friends that I would like to thank for so much. The number of people that I am indebted to has grown over the years. However, there are some that specifically supported me in finalising this thesis. First of all, I would like to thank my two supervisors and very dear friends Håkan Alm and Lena Nilsson. I have learned a lot from their questions, feedback and guidance. I am greatly thankful to Jan Petzäll who commissioned the work that made this thesis possible and patiently waited for the results. I would also like to thank my co-authors to the included papers Colette Nicolle, Joakim Östlund, Håkan Alm and Per Henriksson. Furthermore, the cooperation with Joakim in the joystick projects was great fun and gave me a friend for life. Erik Hollnagel extended and connected the fascinating control loops. Gabriel Helmers gave me the idea to include a couple of introductory examples of the problem addressed in this thesis. Anna Anund kindly read and commented my thesis manuscript. Torbjörn Falkmer contributed developing the ideas that emerged though out this work. John Fulland, Benny Nielsen and Torsten Gunnerius were my connection to the reality. Elisabeth Peterson helped me with all the practical details. Finally, I could not have done this without the support from Anne-Marie who put up with my absent mind and many mistakes, slips and faults.
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### Appendix 1 Abbreviations

<table>
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<tr>
<th>Abbreviation</th>
<th>Explanation</th>
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<tbody>
<tr>
<td>AC</td>
<td>Air Condition</td>
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<td>ACC</td>
<td>Adaptive Cruise Control</td>
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<td>ADA</td>
<td>Americans with Disability Act</td>
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<td>ADAS</td>
<td>Advanced Driver Assistance Systems</td>
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<td>ADED</td>
<td>Association of Driver Educators for the Disabled</td>
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<td>ANOVA</td>
<td>Analysis of variance</td>
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<td>ATT</td>
<td>Advanced Transport Telematics often used as synonym to ITS</td>
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<tr>
<td>CARA</td>
<td>Centre d’adaption à la route pour automobilistes handicapés (Belgium)</td>
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<td>CBR</td>
<td>Cetraal Bureau Rijvaardigheidsbewijzen (the driving license authority in the Netherlands)</td>
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<td>CONSENUS</td>
<td>European IST project (Peters et al., 2004)</td>
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<td>DHR</td>
<td>De Handikappades Riksförbund</td>
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<td>DfT</td>
<td>Department for Transport (Great Britian) (formerly DOT)</td>
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<td>DOT</td>
<td>Department Of Transport (Great Britian)</td>
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<td>DSA</td>
<td>Ministry of Health and Social Affairs (Socialdepartementet)</td>
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<td>ECG</td>
<td>Electrocardiogram</td>
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<td>EMG</td>
<td>Electromyogram</td>
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<td>EC</td>
<td>European Community</td>
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<td>EDDIT</td>
<td>Elderly and Disabled Drivers Information Telematics (EU project in the DRIVE II programme)</td>
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<td>GADGET</td>
<td>European project on Driver Training and Education</td>
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<td>GDE</td>
<td>Goals for Driver Education</td>
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<td>GIDS</td>
<td>Generic Intelligent Driver Support (EU project in the DRIVE II programme)</td>
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<td>HFES - EC</td>
<td>Human Factors and Ergonomic Society – European Chapter</td>
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<td>HMI</td>
<td>Human Machine Interaction</td>
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<td>HRV</td>
<td>Heart Rate Variability</td>
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<td>ICD</td>
<td>International Classification of Diseases (WHO)</td>
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<td>ICF</td>
<td>International Classification of Functions (WHO)</td>
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<td>ICIDH</td>
<td>International Classification of Impairments, Disabilities, and Handicaps (WHO)</td>
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<td>ICTTP</td>
<td>International Conference on Traffic &amp; Transport Psychology</td>
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<td>IST</td>
<td>Information Society Technology (EC)</td>
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<td>ITS</td>
<td>Intelligent Transport Systems i.e. IT based support systems for transport applications. See also ATT and ADAS</td>
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<td>Abbreviation</td>
<td>Explanation</td>
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<tr>
<td>MIRA</td>
<td>Motor Industries Research Association</td>
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<td>MS</td>
<td>Multiple Sclerosis</td>
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<td>NASA-RTLX</td>
<td>NASA – Raw Task Load Index A simplified form of the NASA-TLX without pair wise comparison. (Subjective workload rating scale)</td>
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<td>NHR</td>
<td>Neurologiskt Handikappades Riksförbund</td>
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<td>NHTSA</td>
<td>National Highway Traffic Safety Administration (United States)</td>
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<td>NSCISC</td>
<td>National Spinal Cord Injury Statistical Center (USA)</td>
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<td>NSIB</td>
<td>National Social Insurance Board (Riksförsäkringsverket)</td>
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<td>RBU</td>
<td>Riksförbundet för Rörelsehindrade Barn och Ungdomar</td>
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<td>RRV</td>
<td>The Swedish National Audit Office (Riksrevisorsverket)</td>
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<td>RTP</td>
<td>Riksförbundet för Trafik- och Polioskadade</td>
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<tr>
<td>SCI</td>
<td>Spinal Cord Injury</td>
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<td>SD</td>
<td>Standard Deviation</td>
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<td>SDLP</td>
<td>Standard Deviation of Lateral Position</td>
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<td>SIF</td>
<td>Swedish Inheritance Fund</td>
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<tr>
<td>SMVIC</td>
<td>The Swedish Motor Vehicle Inspection Company (AB Svensk Bilprovning)</td>
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<td>SNRA</td>
<td>Swedish National Road Administration (Vägverket)</td>
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<td>TELAID</td>
<td>TELematics Applications for the Integration of Drivers with Special Needs (EU project in the DRIVE II programme)</td>
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<td>TELSCAN</td>
<td>TELematic Standards and Coordination of ATT systems in relation to elderly and disabled travellers (EU project in the 4th framework)</td>
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<td>TFD</td>
<td>Transport research delegation (Transportforskningdelegationen)</td>
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<tr>
<td>TH</td>
<td>Time Headway is calculated as the headway distance to lead vehicle divided by the speed of the own car</td>
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<tr>
<td>TLC</td>
<td>Time-to-line-crossing - TLC is measured as the distance to line crossing along the vehicles path divided by the speed of the vehicle.</td>
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<td>TRIP</td>
<td>Test Ride for Investigating Practical Fitness to Drive – a practical driving test developed by e.g. Wiebo Brower</td>
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<tr>
<td>TTC</td>
<td>Time-to-collision - TTC is computed as the headway distance divided by the speed difference between the vehicles or the approaching speed</td>
</tr>
<tr>
<td>TTO</td>
<td>Time-to-obstacle – performance measure similar to TTC and TLC but generic</td>
</tr>
<tr>
<td>WHO</td>
<td>World Health Organisation</td>
</tr>
</tbody>
</table>
Paper I

Driving performance and workload assessment of drivers with tetraplegia – an adaptation evaluation framework¹

Driving performance and workload assessment of drivers with tetraplegia – an adaptation evaluation framework

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Abstract
The purpose of this study was to establish a baseline for further research on adaptation evaluation for drivers with disabilities. Driving performance and workload for 26 drivers with Spinal Cord Injuries (tetraplegia) was studied and compared to a matched group of able-bodied drivers in a driving simulator. Drivers with tetraplegia used two types of hand-operated controls for accelerating and braking. Able-bodied drivers drove with standard pedals. The drivers with tetraplegia performed the driving task equally well as the control group but had a slightly longer reaction time (10%). Workload assessment revealed that drivers with tetraplegia experienced a significantly greater time pressure and spent more effort than did the able-bodied drivers. They were also more tired from braking and accelerating. The drivers with tetraplegia using separate levers had greater standard deviation in lateral lane position (7 cm), while those using a combined lever were more tired from braking and accelerating. Observed differences could be interpreted as indicators of insufficient adaptation.

Keywords: adaptation evaluation, assessment, driving performance, driving simulator, spinal cord injury.

Introduction
In the USA, the annual incidence rate for Spinal Cord Injuries (SCI) is 30 - 40 cases per million inhabitants or 8,000 - 10,000 SCI patients annually according to the National Spinal Cord Injury Statistical Center (NSCISC), ((NSCISC), 2000). This number is probably too low due to significant under-reporting according to NSCISC. Corresponding incidence rate for Sweden is 13 cases per million people annually (Peters, 1998b). SCI is a typical young male diagnosis. Median age at injury is approximately 25 years and over 80 % are males. The current trend is that both average age at accident and female proportion increasing2. Between 35 - 50 % of the injuries are caused by traffic accidents, but also falls (20 -30 %) and sport accidents (10 - 20%) contribute significantly.

Approximately 50 percent of the SCI population consists of paraplegics and the other 50 are tetraplegics ((NSCISC), 2000). All tetraplegics and most paraplegics depend on mobility aids such as wheelchairs for short-range transportation. If the injury is located below the fourth cervical vertebra and if there are no additional complications, the

2 Kreuter M. Spinal Cord Injuries - Causes, Gender and Age distribution. Spinal Unit at the Sahlgrenska Hospital, Gothenburg, Sweden, personal communication, 1997.
prospects of becoming a licensed driver are good, given the right adaptation is provided (Peters, 1998a). The opportunity to independently drive a car substantially contributes to increase quality of life and the possibilities to participate in daily life activities (Örne, Hallin, & Kreuter, 1997), (Dahlstrand, Dahl, Andersson, Kreuter, & Peters, 1998). Public transportation cannot offer the same level of flexibility and independence.

Standard-production cars are not designed for drivers with disabilities and usually have to be adapted according to the individual driver’s resources and limitations. Koppa (1990) identified three different areas where physically disabled drivers require provision: ingress/egress, primary and secondary controls, and occupant protection. A driver with disabilities provided with an adequate adaptation is not a handicapped driver in the sense that he or she is a poorer driver compared to an able-bodied driver. A handicap is caused by a mismatch between an impaired person’s abilities and the environmental demand (WHO, 1980). The right adaptation should compensate for a driver’s impairment and thus eliminate a potential handicap while the impairment still remains.

There are no common international regulations and requirements on how to adapt cars for drivers with disabilities (Fulland & Peters, 1999). The national differences can be considerable and inconsistent. The national regulations are often incomplete and vague. However, a general rule that usually applies is that a disabled person can be allowed to drive if the disability can be fully compensated by adapting the vehicle. There do exist some general guidelines for car adaptations for drivers with disabilities (DOT, 1992) (SINTEF, 1993) but these are far from comprehensive. Occasionally, tests are carried out to ensure that disabled person’s available resources (e.g. strength, reaction time, and reach) are sufficient and to determine the adaptation needs (Haslegrave, 1988) (Bolduc, 1999). However, there are no standardized evaluation tests that can be used to verify that the right adaptations have been provided (Barnes & Hoyle, 1995) (Fulland & Peters, 1999). Koppa (1990) claimed that a driver with disabilities should be able to operate all vehicle controls at the same performance level as a non-disabled driver in a standard car. This implies that an adaptation evaluation should be based on a comparison with non-disabled drivers driving standard cars. An adaptation evaluation should, at least, consider aspects as crashworthiness (passive safety), functionality (active safety), workload, and comfort/discomfort.

Driving a car is a complex and highly dynamic task and thus it is important to determine which aspects of the driving tasks are critical for drivers with SCI (Verwey, 1994). A widely used driving task model distinguishes three levels: control, maneuver, and strategic (Michon, 1985). The control task concerns the actual vehicle handling, i.e. longitudinal and lateral control of the car. Time constraints at control level are usually below 1 s and reaction time is critical for performance at the control level. It is also a task, which requires more or less continuous attention. The maneuvering level includes interactions with other road users, such as overtaking maneuvers. For these tasks time constants are normally between 1 to 10 s. Trip planning and navigation represent tasks at a strategic level. Such tasks are usually not time critical and the time
frame is usually about 10 s or above. For drivers with SCI we are primarily concerned about the control and maneuver level, where one could expect to find differences between SCI and non-disabled drivers. To safely investigate such differences a driving simulator is suitable. Reaction time to unexpected critical events could be used to assess differences in risk level. Although, drivers with SCI use hand controls, which may improve reaction time (Richter & Hyman, 1974), their impairment may on the other hand increase reaction time (Lings, 1991).

Workload is another critical aspect of the driving task for drivers with SCI. Driving a car is normally not particularly physically loading for non-disabled drivers. But, for a driver with tetraplegia, who has to do with two impaired limbs what a non-disabled individual can use four limbs to do, driving is occasionally experienced as tiresome, even if the car is adapted. As a consequence, many drivers with disabilities avoid driving longer distances (Nicolle et al., 1992). Physical workload and endurance are thus critical factors for drivers with SCI. Furthermore, driver fatigue, which could be a consequence of extended workload, is considered an important factor behind many road accidents (McDonald, 1984). There are basically four different methods to a measure workload: subjective rating methods, physiological methods, and primary or secondary task performance (Wickens, 1992). Subjective rating scales are easy and simple to use but also reliable tools.

The following experiment was carried out based on the discussion above in order to establish a baseline for the development of an adaptation evaluation method. The potential differences between SCI and non-disabled drivers revealed in this experiment could thus be partly explained by insufficient adaptation.

The purpose of the experiment was to examine driver performance and limitations of drivers with tetraplegia and to investigate how different adaptation designs influence the driver’s performance and imposed workload. For this purpose drivers with tetraplegia were compared to matched group of able-bodied drivers. The experimental group was divided into two groups, equal in size, depending on what hand controlled system they used, separate or combined levers for accelerator and brake control. The two groups were identified as single and dual-lever drivers. The purpose was not to assess a certain group drivers with disabilities in order to determine whether they should be restricted or not permitted to drive.

**Method**

**Subjects**
Fifty-two subjects, 26 with tetraplegia and 26 able-bodied, participated in the study. The subjects in the experimental group were all paralyzed from the level of their nipples down to their toes due to a lesion in the cervical region of the spine. The position of lesions varied between subjects from the 5th (C5) to the 7th (C7) cervical vertebra (see Table 1). The character of the lesions varied, between subjects, from complete to incomplete. An experienced driving instructor considered the subjects’ functional impairment to be approximately equal with respect to the kind of adaptation needed for controlling the car. Only 2 of the 26 subjects were female, less than 10
percent, which was somewhat low compared to the overall SCI population (18 percent). The drivers with SCI were between 22 and 60 years old with a median age of 36 years and had driving experience using adapted cars, which varied from 4 to 40 years with a median of 17 years. Their annual driving distance varied between 10,000 and 45,000 km with a median distance of 15,500 thousands km. The subjects were assigned to drive with the same type of hand control they used in their own car.

<table>
<thead>
<tr>
<th>Level</th>
<th>Single-lever drivers</th>
<th>Dual-lever drivers</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>C5-C6</td>
<td>8</td>
<td>6</td>
<td>14</td>
</tr>
<tr>
<td>C6-C7</td>
<td>3</td>
<td>5</td>
<td>8</td>
</tr>
<tr>
<td>C6</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>C7</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
</tbody>
</table>

The control group was selected to individually match the experimental group according to gender (24 males and 2 females), age (24 to 56 years, median 37 years), driving experience (driving license 5 to 36 years, median 17 years), and distance driven per year (10,000 to 45,000 km, median 15,500 km).

**Apparatus**

A dynamic, high fidelity driving simulator was used (23, 24). The simulator consisted of a moving base system, a wide-angle image system, a vibration-generating system, a sound system, and a temperature-regulating system (see Table 2). These systems were controlled to give the impression of actually driving a car.

<table>
<thead>
<tr>
<th>Simulator subsystem</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vibrations</td>
<td></td>
</tr>
<tr>
<td>vertical</td>
<td>5 cm</td>
</tr>
<tr>
<td>longitudinal</td>
<td>7.5 cm</td>
</tr>
<tr>
<td>roll</td>
<td>7 °</td>
</tr>
<tr>
<td>Motion</td>
<td></td>
</tr>
<tr>
<td>pitch</td>
<td>24 °</td>
</tr>
<tr>
<td>roll</td>
<td>24 °</td>
</tr>
<tr>
<td>lateral</td>
<td>3 m</td>
</tr>
<tr>
<td>max. acceleration</td>
<td>0.4 g</td>
</tr>
<tr>
<td>Visual system</td>
<td></td>
</tr>
<tr>
<td>forward field of view</td>
<td>120 ° x 30 °</td>
</tr>
<tr>
<td>resolution</td>
<td>3100 x 625 pixels</td>
</tr>
<tr>
<td>time delay</td>
<td>20 ms</td>
</tr>
</tbody>
</table>

A number of validation studies have successfully been performed in this simulator (Törnros et al., 1997). These studies showed that the moving base system was important for the experienced reality and external validity (see Figure 8.1)
The car body used in the simulator was a front part of a Saab 9000 with an automatic gearbox. Noise, infra-sound and vibration levels inside the car corresponded to what is found in modern passenger cars. As the entrance to the car was 2 meters above ground level, a wheelchair lift was installed to make it accessible. A ramp outside the car body was positioned so that the wheelchair and the driver's seat were at the same level to facilitate the transfer. Some SCI subjects used a sliding plate to transfer to the driver's seat. If a subject requested it, an experimental leader would give help to transfer.

Two commonly used hand controls for accelerating and braking were installed in the simulator. This facilitated the recruitment of SCI subjects. The hand controls were principally different in design as one had two separate levers and the other one combined lever for accelerating and braking (see Figure 2). The positions of the two hand controls were also different. The combined lever system was operated by pushing the lever for braking and pulling to accelerate. The system with separate levers was mounted on the steering column. The braking lever was operated by pushing it forward, while the driver accelerated by moving the other lever radially downwards. Both systems had their pros and cons. With the single-lever system the driver did not have to switch from one lever to the other in order to control accelerator and brake. On the other hand, the motion of the lever required to change from speed control to braking could prolong reaction time. Also, the position of the lever made it impossible for the driver to use more than one hand for steering. The dual-lever system let the driver have two hands on the steering wheel, but on the other hand speed control could interfere with steering control. Furthermore, the driver had to transfer from accelerator lever to brake lever in a critical situation, which could prolong reaction time. Which system the driver will select in his/her own car depends very much on previous
experience or recommendations from providers, friends or individual traffic inspectors. None of the systems are specifically considered being superior to the other by responsible authorities. In addition to the hand controls, one of two types of steering knobs was mounted on the steering wheel if the subject had such an adaptation in his/her own car.

![Two hand controls](image)

Figure 2 The two hand controls used in the experiment, to the right the single-lever system and to the left the system with separate levers accelerating and braking. The empty arrows indicate the direction for braking, and the filled arrows for accelerating (from SINTEF, 1991) with permission)

The power-assisted brakes were adapted if a SCI subject was not able to exert the force needed to lock the brakes (380 N) on the brake lever. "Comfortable" braking level was recorded and if the recorded force was greater than 75 percent of the subject's maximum force (< 380 N), then the brakes were adapted so the exerting maximum force corresponded to 380 N. If "comfortable" braking instead resulted in a force less than 75 percent of the subject's maximum force (< 380 N), the brakes were adapted so the "comfortable" level corresponded to 75 percent of maximum force, and the maximum force was scaled to correspond to 380 N. The power-assisted steering could be augmented so that only half the force was required to steer. This was done if required and if the driver was used to such an adaptation from his/her own car. This procedure was derived from praxis used by experienced car adaptation companies.

**The driving task**

All subjects drove the same route and were exposed to the same situations and events. The route was 80 km long and consisted of two consecutive sections, each 40 km, with the same geometry. The road was a 2-lane, 9 m wide asphalt road with high friction. The weather was slightly cloudy with an average sight distance of 400 m.

Ninety-six, 48 in each half, oncoming cars appeared randomly along the route. The purpose was to increase workload and realism. Twenty-four cars were parked on the right side along the route, 12 along each half. In 4 of these situations, oncoming cars were encountered 40 m before passing the parked cars. A specific situation was
created to force the subjects to make an evasive maneuver. On four occasions parked cars on the right side of the road started to drive and turn left as the driver approached.

Visual stimuli, presented at the left side of the road, were used to simulate unexpected traffic events. The stimuli were 4 x 4 cm red or yellow squares presented 2.5 m from the driver's eyes representing an approximate sight angle of 1°. The subjects were instructed to brake as fast as possible for red squares and to ignore yellow squares. These situations occurred eight times in random order, four red and four yellow squares, for each subject.

**Measures**
A number of dependent variables were used to analyze driving performance and workload. Data were calculated and recorded, with a frequency of 2 Hz. Questionnaires were used to capture subjective data and background information. Means were calculated for individual subjects, and standard deviation (S.D.) was used as a measure of variation.

Speed, speed variation, lateral position, variation of lateral position, distance to overtake cars and reaction time were used as performance measures. Lateral position was calculated as the distance from the centerline of the road to lateral position of center of the steering wheel. Standard deviation of lateral position was used as a measure of the drivers steering control. Brake reaction time in seconds was calculated as the time elapsed from display of visual stimulus until the brake (foot or hand-controlled) was depressed with a force greater or equal to 0.05 N. The resolution was 20 ms. If there was no response within 5 s, the stimulus was removed. Mean reaction time was calculated for each subject.

Workload was measured with a subjective rating scale. The Task Load Index, NASA-TLX (Hart & Staveland, 1988) that proved to be superior to other rating scales in a study by Hill (1992) was used in a simplified form (Raw Task Load Index) NASA-RTLX (Byers et al., 1989) to assess the subjects' overall workload. The NASA – TLX have been used and validated for broad variety of activities and is frequently used traffic safety research. The subjects estimated six workload factors: *mental demand, physical demand, time pressure, performance, effort* and *frustration levels* on a continuous scale ranging from very low to very high (0 - 100) after completion of the driving task. The subjects rated their workload based on six different questions like e.g. “How much physical activity was required (e.g. pushing, pulling, turning, controlling, activating etc.)? Was the task easy or demanding, slow or brisk, slack or strenuous, restful or laborious?” (Physical demand) and “How hard did you have to work (mentally and physically) to accomplish your level of performance?” (Effort).

Static force capacity was measured immediately before and after driving. The SCI subjects exerted a static force on the brake lever and kept it for 20 seconds, then released the pressure and rested for 5 seconds. This was repeated five times before and after driving. The initial phase, 5 seconds, of the force measuring was excluded and
only the steady state or declining phase, 5 - 20 seconds, was used to calculate a mean force capacity for each subject.

Questions concerning gender, age, driver’s license, annual distance driven, driving experience, and driving habits were answered by all subjects. The SCI subjects also answered questions concerning their injury and what kind of adaptations they had in their own cars. Experienced realism and specific questions about steering, braking and accelerating control were asked in a separate questionnaire.

Results

Driving performance

Group means were calculated and one-way ANOVAs were used to evaluate the results and a significance level was set to $p < 0.05$. The average speed over the total distance for drivers with tetraplegia was 91.3 km/h, while it was 88.4 km/h for the control group. Mean speed for the two SCI subgroups was 93.4 km/h and 89.2 km/h for single and dual-lever users respectively. However, none of these differences were significant. Furthermore, analyzes of variation in speed revealed no significant differences, between the groups, neither for the total test route nor for the two 40 km halves separately. As the two sections of the route were equal, data on speed variation per section was also analyzed. It turned out that variation in speed was higher for all groups during the second part of the route (see Table 3). The differences, however, were non significant.

Table 3 Mean and variation (standard deviation) in speed (km/h) for first and second half of the experimental route

<table>
<thead>
<tr>
<th>Group</th>
<th>First 40 km (mean/sd)</th>
<th>Second 40 km (mean/sd)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tetraplegics</td>
<td></td>
<td></td>
</tr>
<tr>
<td>single-lever</td>
<td>92.8 / 8.74</td>
<td>94.0 / 10.75</td>
</tr>
<tr>
<td>dual-lever</td>
<td>89.2 / 9.64</td>
<td>89.2 / 11.90</td>
</tr>
<tr>
<td>Total</td>
<td>91.0 / 9.19</td>
<td>91.6 / 11.32</td>
</tr>
<tr>
<td>Able-bodied</td>
<td></td>
<td></td>
</tr>
<tr>
<td>“single-lever controls”</td>
<td>88.9 / 9.35</td>
<td>89.1 / 11.19</td>
</tr>
<tr>
<td>“dual-lever controls”</td>
<td>86.8 / 10.64</td>
<td>89.0 / 12.65</td>
</tr>
<tr>
<td>Total</td>
<td>87.9 / 10.00</td>
<td>89.0 / 11.92</td>
</tr>
</tbody>
</table>

The results of the choice reaction-braking task, with red and yellow square stimuli are shown in Table 4. Mean reaction time for was .90 s and for the control group .80 s. The difference between drivers with tetraplegia and control drivers, 0.10 s was significant [$F(1,50)=6.53$, $p=0.014$]. The difference between the two groups of drivers with tetraplegia and their respective control groups was only significant for the dual-lever group [$F(1,24)=4.35$, $p=0.048$]. However, the difference between single and dual-lever groups was not significant.
Table 4 Average brake reaction times for experimental and control group

<table>
<thead>
<tr>
<th>Group</th>
<th>Mean reaction time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tetraplegics</td>
<td></td>
</tr>
<tr>
<td>single-lever</td>
<td>.88</td>
</tr>
<tr>
<td>dual-lever</td>
<td>.93</td>
</tr>
<tr>
<td>Total</td>
<td>.90</td>
</tr>
<tr>
<td>Able-bodied</td>
<td></td>
</tr>
<tr>
<td>“single-lever controls”</td>
<td>.81</td>
</tr>
<tr>
<td>“dual-lever controls”</td>
<td>.79</td>
</tr>
<tr>
<td>Total</td>
<td>.80</td>
</tr>
</tbody>
</table>

The mean lateral position for all straight sections of the route was calculated for each subject. Only straight sections were used for this analysis, as curve taking can be very individual, a difference of no relevance in this case. The differences were not significant, neither between tetraplegics and controls, nor between the two subgroups of tetraplegics.

The mean variation in lateral lane position was calculated over all straight sections of the route for each subject. There was no significant difference between the drivers with tetraplegia, S.D. = 0.43 m, and the control group S.D. = 0.47 m. However, the tetraplegics driving with dual-lever controls had a variation in lateral lane position which was S.D. = 0.47 m. This was significantly greater than for those using the single-lever control, S.D. = 0.40 m, \[F(1,24)=5.30, p=0.030\]. Steering performance was also analyzed while the subjects braked in response to the red squares, but no significant differences were found.

The evasive maneuvers were analyzed with the following derived measures: minimum passing distance to parked car, speed when passing the parked car, maximum left position during overtaking. There were no significant differences, neither between experimental and control group, nor between the two experimental subgroups.

**Workload, Endurance and Questionnaires**

Group means of the six workload factors, mental demand, physical demand, time pressure, performance, effort and frustration, of NASA-RTLX were calculated and analyzed (see Figure 3). The subjects with tetraplegia estimated their effort as greater and experienced a greater time pressure compared to the control group. These differences were significant for time pressure \[F(1,50)=8.42, p=0.006\] and effort \[F(1,50)=4.01, p=0.050\]. Other differences between the groups were not significant. The two subgroups with SCI did not differ significantly in their ratings.
Static force measurements were taken for drivers with SCI before and after the driving task using the brake levers (see Figure 2). The average force before was 448 N for the single-lever users and 349 N for the dual-lever users. This difference was significant [F(1,24)=7.59, p=0.011]. Corresponding forces after driving were 428 N and 315 N respectively which also was significantly different [F(1,24)=12.88, p=0.001]. The difference between initial and final force levels for the two groups were, however, not significant. The ratio between before and after mean forces was .97 (single) and .92 (dual). Also, this difference was non-significant.

The subjects answered a specific question, "Do you think it was tiring to brake and accelerate?" with a rating on a scale ranging from 1 for "very tiring" to 7 for "not at all tiring". The average for the tetraplegic group was 5.69 and the corresponding value for the control group was 6.84. This difference was significant [F(1,50)=12.20, p=0.001]. The subjects driving with the single-lever control thought it was physically more tiring to brake and accelerate, mean 5.08, compared to the dual-lever group, mean 6.31. This difference was significant [F(1,24)=4.10, p=0.050]

Steering and speed performance data was also considered to be a possible way to reveal signs of fatigue. Increased variation in lateral and longitudinal control would
then indicate possible signs of fatigue due to physical workload. The analysis of speed control showed that speed variation was higher for the second part of the test route, but the differences were not significant.

The subjects were asked questions of how well they thought they could steer, brake, and accelerate in the simulator. They gave their answers on a 7-point scale ranging from "not at all well" to "very well". They were also asked about the realism in the simulator and gave their answers on the same type of scale ranging from "not at all realistic" to "very realistic". The results are given in Table 5. The only significant difference was that the single-lever drivers thought that they could control the brake better compared to the other group of drivers with tetraplegia [F(1,24)=5.27, p=0.031].

Table 5 Group means for answers on questions concerning steering, braking, accelerating and simulator realism

<table>
<thead>
<tr>
<th>Group</th>
<th>Steer</th>
<th>Brake</th>
<th>Accelerate</th>
<th>Realism</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tetraplegics</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>single-lever</td>
<td>6.2</td>
<td>6.8</td>
<td>6.2</td>
<td>4.9</td>
</tr>
<tr>
<td>dual-lever</td>
<td>6.5</td>
<td>5.6</td>
<td>5.5</td>
<td>5.4</td>
</tr>
<tr>
<td>Total</td>
<td>6.3</td>
<td>6.2</td>
<td>5.8</td>
<td>5.2</td>
</tr>
<tr>
<td>Able-bodied</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>“single-lever controls”</td>
<td>6.4</td>
<td>6.2</td>
<td>5.8</td>
<td>4.8</td>
</tr>
<tr>
<td>“dual-lever controls”</td>
<td>6.2</td>
<td>5.4</td>
<td>6.1</td>
<td>5.1</td>
</tr>
<tr>
<td>Total</td>
<td>6.3</td>
<td>5.8</td>
<td>5.9</td>
<td>5.0</td>
</tr>
</tbody>
</table>

**Discussion**

Driving performance of drivers with tetraplegia was evaluated from safety and workload point of view. In such an evaluation it is important that the results are related to driving as experienced on the road, and that relevant measures are used (Verwey, 1994). The driving task, in this experiment, included speed control, road following, interacting with other road users, and reacting to unexpected events. Performance, reaction time, workload and endurance were used to assess driver behavior and condition. For high controllability and safety reasons the experiment was performed in a dynamic driving simulator. The motion system of the simulator has shown to contribute to the experience of reality (Törnros et al., 1997). This was considered important with respect to drivers with tetraplegia, as they are, due to their impairment, sensitive to forces, which may influence their trunk stability.

**Driving performance**

Since there are no norms that can be used to determine whether specific driving behavior is safe or not, a matched group of able-bodied drivers using conventional car controls were used as reference. From a traffic safety point of view, drivers with tetraplegia are required to perform the driving task equally well as able-bodied drivers in standard cars (Vägverket, 1996b). Regulations specify that the car should be adapted so that the driver’s impairment is fully compensated. Even if the car is adapted
it is likely that drivers with tetraplegia will be closer to the limit of their resources. This hypothesis is supported by the finding that drivers with disabilities avoid long distance driving (Nicolle et al., 1992). Inappropriate or inadequate adaptation could lead to severe consequences beyond limited mobility. Too many adaptations do not fulfill the adaptation requirements as specified by Koppa (1990). All of these requirements were not possible to test in this setting, but focus was on control and maneuver performance in a rural road environment.

The analysis of the general driving performance measures such as speed and lateral lane position did not reveal any significant differences between the tetraplegic and control group. The type of hand control used had no influence either. Thus the gross overall-driving behavior was similar for the two groups. This supports the proposition that the adaptation was adequate.

The average speed level did not differ significantly between the groups, which indicate that they all drove quite similar with respect to speed choice. The standard deviation in speed was greater for the second half of the 80 km long test route for all drivers. Even though this difference was not significant, it seems to indicate that subjects deteriorated in their speed control and this could be a sign of fatigue. It was also noted that for the group driving with the dual-lever system, this difference (see Table 3) was almost significant (p=0.054).

Considering the reaction time results, drivers with tetraplegia were about 10% slower than able-bodied drivers. It could be debated whether this result was an indication of inadequate adaptation with possible safety consequences or if it should be considered as an acceptable deviation. Reaction times for both groups seemed to be fully acceptable compared to other findings. Green (29) analyzed reaction time results derived from simulator studies, controlled road studies and naturalistic observation and concluded that brake reaction times varies between 0.7 and 1.5 s depending on the driver’s expectation. Subjects in this study were instructed to brake as fast as possible and were fairly prepared to the events. Nilsson and Alm (1991) found in a simulator study that young drivers had a mean reaction time of 0.95 s compared to a mean of 1.34 s for a group of elderly (+65) driver. Johansson & Rumar (1971) reported from an on the road study with more than 300 drivers that the median brake reaction time was 0.9 s. Thus, it can be argued that the adaptation, hand controls, compensated for the drivers’ disabilities.

It was expected that the reaction times for the group driving with the single-lever would be shorter compared to those driving with the separate brake lever. For instance Richter and Hyman (17) found that reaction time improved by 25% with a hand-operated brake controls because drivers did not have to move from the accelerator to the brake. Even if there was a difference (see Table 4) in that direction it was not significant. However, the difference between the tetraplegic and the control groups seems to be most pronounced for those driving with the dual-lever system. The difference between this group and its control group was significant. This seems to
suggest that there was an influence on reaction time, which could be attributed to the design of the controls.

There were no differences in average lateral lane position for straight sections between the groups, which suggest that all four groups positioned the car in the lane in a similar fashion. The variation (S.D.) in lateral lane position showed, though, an interesting result. It was expected that driving with the single-lever would have some negative impact on the steering control, as the lever’s location implies "one hand steering". Instead the tetraplegics using the dual-lever control had 0.07 m greater S.D. in lateral lane position. One explanation for this result can be interference between speed control and steering control. The dual-lever speed control, placed on the steering column, is operated radially and permits the driver to keep the right hand simultaneously on both the steering wheel and the speed control. However, there was no difference, in total, between the drivers with tetraplegia and the able-bodied drivers. This result also supports the suggestion that adaptation design differences can influence driving performance. In order to further develop the lateral control performance as a measure to investigate adaptation design it would be valuable to explore the use of the time-to-line-crossing (TLC) concept (Godthelp, 1988; Godthelp et al., 1984). The TLC is a time-dependent measure, which can be used to investigate steering control performance.

The analysis of the evasive maneuvers did not reveal any significant differences between any of the groups. The idea was to investigate a task, which required increased simultaneous lateral and longitudinal control of the car in order to find out how well the different adaptations supported the drivers in such a situation. There are at least three possible explanations to this result. One is that the maneuvers were too easy to reveal any differences. Another possibility is that the situation included an oncoming car that was controlled in a way that the meeting point was the same for all subjects. This forced in a way the drivers into similar maneuver patterns. Finally, both hand control systems could be seen as adequate. A more demanding maneuver, for example, a double lane change could possibly be used for further investigations. Such a task was used in a closed-track experiment with drivers who were severely disabled and who drove their own four-way joystick-controlled cars and revealed some difficulties that were considered to be caused by the adaptation (Östlund & Peters, 1999).

**Workload, endurance and questionnaires**
The workload assessment included both mental and physical aspects of the driving task. Of the six workload factors of NASA - RTLX three -- mental demand, physical demand, and frustration -- were, surprisingly, greater for the able-bodied drivers compared to the tetraplegics. These differences, however, were not significant. The only significant difference was that drivers with tetraplegia experienced a greater time pressure and exerted more effort. This seems to indicate that the tetraplegics found the driving task more loading than did the able-bodied drivers. This suggestion was supported by the result of the explicit question "Do you think it was tiring to brake and accelerate?" The result was in accordance with what was found in interviews with
drivers with disabilities (Nicolle et al., 1992). The analysis of the NASA - RTLX did not reveal any differences between the two groups of tetraplegics. However, drivers using the single-lever control indicated, in their answers to the question mentioned above, a higher degree of tiredness. This was probably due to the position of the control lever, between the front seats, where there was no support for the arm, which led to an uncomfortable arm posture. The results from the static force measures did, however, not show any significant decrease force capacity. Thus, the experienced tiredness cannot be explained by local fatigue in the driver’s arm. Changes in speed variation (S.D.) as an indicator of increased workload for the single-lever drivers did not support the finding of greater tiredness for the group. It was found that speed variation increased more for the dual-lever users, but this was probably due to interference between speed and steering control for that adaptation.

The experienced realism in the simulator is important for how valid the findings are for real driving conditions. The simulator used in this study is one of the few driving simulators in which validations studies have been successfully performed (Törnros et al., 1997). The analysis of the responses to the questions of steering, braking and accelerating realism did not show any significant differences between the groups. But the results, 5.5 – 6.8 on a 7-graded scale, indicated that the drivers experienced simulator driving as quite naturalistic (Table 5). This was also supported by answer to the question of experienced realism in the simulator. The result was good considering the limited possibilities for adapting the simulator. Differences between the simulator and the subjects’ own individually adapted car may also have contributed to differences between the groups. This is not however a major problem as the objective was not to assess drivers, but adaptations. Furthermore, it can be noted that the scores for steering is somewhat higher compared to braking and accelerating (Table 5). This is consistent with experiences from other experiments in the simulator and can possibly be explained by the differences in the lateral and longitudinal motion system (Figure 1).

Conclusions
There were no great differences in general driving behavior between the groups. However, drivers with tetraplegia had a somewhat longer reaction time compared to the control group. They also experienced the driving task as more loading and spent more effort to perform at the level they did. The observed differences could be an indication of insufficient adaptation. Differences in driving performance and workload between the two subgroups of drivers with tetraplegia could be interpreted as indications of design imperfections in the hand control systems used in this study. However, the method applied in this experiment needs to be further developed and refined before it can be used to evaluate different adaptations solutions.

References


Adaptation Evaluation – An Adaptive Cruise Control (ACC) system used by Drivers with Lower Limb Disabilities\(^1\)

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Adaptation Evaluation – An Adaptive Cruise Control (ACC) system used by Drivers with Lower Limb Disabilities

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Abstract
Twenty subjects with lower limb disabilities participated in a simulator study. The purpose of the study was to investigate how an Adaptive Cruise Control (ACC) system together with two different hand controls for accelerator and brake influenced workload, comfort and driving behaviour and to further develop a method to evaluate vehicle adaptations for drivers with disabilities. The installed ACC system could maintain a constant speed selected and set by the driver and it also adapted speed in order to keep a safe distance to a leading vehicle. Furthermore, it included a stop-and-go function. Two common types of hand controls for accelerator and brake were used. The hand controls were different both with respect to function, single or dual levers, and position, on the steering column or between the front seats. The subjects were all experienced drivers of adapted cars equipped with hand controls. All subjects drove 100 km at two occasions, with and without the ACC system available but with the same hand control. Subjective workload was found to be significantly lower and performance better for the ACC condition. The difference in speed variation between manual and ACC supported driving increased with the distance driven which seems to support the previous finding. The subjects thought they could control both speed and distance to leading vehicles better while the ACC was available. ACC driving did not influence reaction time, speed level, lateral position or variation in lateral position. Headway during car following situations was shorter for the ACC condition compared to manual driving. The ACC was well received, trusted and wanted. It was concluded that the ACC system substantially decreased workload, increased comfort and did not influence safety negatively. The only difference found between the two types of hand controls was that drivers using the dual lever system had less variation in lateral position. The applied evaluation method proved to be useful but needs to be further developed.

Keywords: Disabled drivers, Adaptation evaluation, Adaptive cruise control, Hand control, Driving simulator

1 Introduction
Mobility impairments are by far the most common type of impairment (Elkind, 1990; Sandhu & Wood, 1990). Many mobility-impaired people can achieve mobility and independence with access to a car they can drive on their own. Driving can also contribute to improve quality of life and health (Fulland & Peters, 1999; Peters, 1998). However, many people with mobility impairments cannot use a conventional car unless it adapted. The objective of car adaptations
is to fully compensate for the driver's disabilities. Routines and regulations for adapting passenger cars vary a lot between countries and there are no standardized requirements even within the European Community (EC) (Fullaand & Peters, 1999). Furthermore, today there does not exist any adaptation evaluation aimed at investigating whether the adaptation objectives have been met. In case an evaluation is performed it is often done ad hoc and is neither comprehensive nor consistent and finally, it is usually not documented. The long-term goal, of which the current study was a part, is to develop a useful and user-centered evaluation method for adapted cars, which include aspects like function, safety, comfort and trust (Peters et al., 2000). The current study focuses on the first three aspects and the users' opinion.

Driving is a complex and dynamic task, which can be modelled in many ways. An adaptation evaluation should be concerned with the various demands the driving task impose on the driver. The driving task can be described as tasks on three different levels: strategical, tactical and operational (Michon, 1985) and the driver’s behaviour as three corresponding levels (knowledge, rule and skill based) behaviour (Rasmussen, 1983). An adaptation evaluation for experienced drivers with lower limb impairments should, first of all, focuses on the tactical and operational demand levels together with rule and skill based behaviour. This guided the design of the present evaluation.

An adaptation should provide the driver with a possibility to safely and efficiently control the vehicle. Safety is prerequisite for independent mobility for the targeted group (Delén, 1999). Only active safety, i.e. safe driving behaviour, was considered in this study. Passive safety was left out. Comparative methods were used for the evaluation, as there does not exist any well-defined and useful criteria for safe driving behaviour. The same driving behaviour requirements apply for drivers of adapted cars as for any other driver on the road (Vägverket, 1996). Thus, comparisons should be made relative to able-bodied driver of standard production cars (Koppa, 1990). Furthermore, a comparative method can be used to evaluate different adaptation solutions, as done in this study.

Drivers of adapted cars do not seem to be involved in more accidents than other drivers. On the contrary, it seems like they are less involved (Haslagrave, 1986; Henriksson, 2001; Lääperi et al., 1995). However, underreporting due to e.g. the risk that drivers who feel unsafe give up driving can possibly be a problem. In that case, safety is maintained at the cost of reduced mobility. It seems likely that drivers of adapted cars drive more careful well aware of their limitations and their dependence on the car. However, this cannot be taken as an excuse for accepting lower driving performance requirements compared to other drivers (Peters et al., 2000). If the requirements are not met, this should be interpreted, as the adaptation was not sufficient. A suitable adaptation should make optimal use of the available resources of the driver in order to minimize the physical and mental load on the driver (Verwey, 1994).

The driving task designed for an adaptation evaluation has to be composed to include relevant, critical but still realistic subtasks. A distinction can be made between driving performance and driving behaviour (Evans, 1991). Driving performance is the upper limit of what a driver can do while driving behaviour reflect what the driver actually does. Both performance and behaviour are of interest for an adaptation evaluation. A break reaction task can be used to measure performance but reaction times will depend very much on the driver’s expectations (Green, 2000) and also on the driving task context and complexity. As the driving task complexity increases the demands on the driver will raise and finally resource allocation becomes critical. This may prolong reaction times (Alm & Nilsson, 1995). When
demands are low, driving can be highly automated and observed reaction times can come closer to measure performance under the assumption that the driver is alert. Lateral and longitudinal control of the car is also critical to assess in an adaptation evaluation.

Hand controls systems for braking and accelerating can be implemented in many different ways. Two important aspects of hand controls are: position and whether the controls are combined or separate. A system where the controls are placed near the steering wheel so that both hands can be used for steering could facilitate the steering control but also interfere with it. A system where the controls are combined could facilitate the speed/brake control (no grip shift) but could also prolong brake reaction times (motion time). Finding the optimal solution with respect to both function and position can be difficult.

Drivers with lower limb impairments, which are so severe that the driver can only use the upper limbs in order to drive often experience a high load on the upper limbs (Peters, 2001). Both steering and speed keeping require continuous control with the risk of static and uncomfortable postures that could have to be maintained over long periods. The possibilities to off-load their upper limbs are often limited and thus, strain and discomfort can become a serious problem. Thus, drivers of adapted cars often avoid long distance driving and restrict their mobility (Nicolle, Peters, & Vossen, 1994). In summary, it seems like drivers of adapted cars drive just as safe as others but at a higher cost in workload and limited mobility. One way of reducing the load on the driver could be to install a Cruise Control (CC). A CC is a support system, which keeps a constant speed selected by the driver. One disadvantage of a conventional CC is that it only holds a constant speed independent on the traffic environment, which limits the usability. This problem is solved with an Adaptive Cruise Controller (ACC). An ACC can adjust speed so that slower preceding vehicles can be followed at a "safe" distance. The function is realized with a distance-measuring device at the front of the car. The ACC maintains a speed dependent distance to a leading vehicle by controlling both accelerator and brake. The system tested in this study had also a stop-and-go function implemented. An ACC should be able to reduce the load on the driver and thus enhance mobility. Apart from being a comfort system ACC driving can have both positive, reduced short headways (Nilsson & Nåbo, 1995) and negative effects, over reliance (Nilsson, 1995).

The main purposes of this study were to investigate the influence ACC driving can have on comfort, behaviour, and workload for drivers who depend on hand operated controls and to further develop a method to evaluate vehicle adaptations for drivers disabilities. Two types of hand control systems for accelerator and brake, identified as single respectively dual lever system, were installed and used in this study.

2 Method
The experiment was performed as a two-by-two mixed factorial design. Within-subject design was used for the ACC condition and between-subject design with respect to hand control system used (Table 1). The order of ACC condition was counterbalanced.

Table 1 Experimental design

<table>
<thead>
<tr>
<th></th>
<th>Single lever system</th>
<th>Dual lever system</th>
</tr>
</thead>
<tbody>
<tr>
<td>With ACC</td>
<td>10 subjects</td>
<td>10 subjects</td>
</tr>
<tr>
<td>Without ACC</td>
<td>10 subjects</td>
<td>10 subjects</td>
</tr>
</tbody>
</table>
2.1 Subjects
Twenty subjects, seventeen men and three women, participated in the study. Their mean age was 39.8 years with a range of 19 to 60 years. All subjects had lower limb disorders, which made it impossible for them to drive conventional cars. Seventeen were paraplegics with complete paresis in their lower limbs caused by a spinal cord lesion at mid trunk level. Two subjects were double leg amputees and one had spina bifida. All subjects had full strength and mobility in their upper limbs. All subjects were licensed drivers with a driving experience of adapted cars ranging from 2 to 17 years with a mean of 9.7 years. The inclusion criteria for subjects were that he or she had at least 40,000 km experience of driving adapted cars. The youngest subject, 19 years, had driven 60,000 km over a two-year period. The average annual driven distance was 22,200 km. The subjects drove with the type of hand control with which they were most experienced.

2.2 Apparatus
A dynamic, high-fidelity driving simulator was used in this study (Nilsson, 1989; Nordmark, 1990). The simulator consisted of six subsystems. The vehicle was modelled in the computer system and the moving base system simulated accelerations in three directions through roll, pitch and linear lateral motions. The visual system presented the external scenario in the form of computer-generated graphics on a 120° wide screen, 2.5 meters in front of the driver. The sound system generated noise and infrasounds that resembles the internal environment in a modern passenger car. The vibration system simulated the sensations the driver experience from the contact between the road and the vehicle. A temperature system controlled the air temperature in the driver's cab. A number of validation studies have successfully been performed in this simulator (Törnros et al., 1997). These studies showed that the moving base system was important for the experienced reality and external validity (see Figure 1).

![Figure 1 The motion system of the driving simulator](image)
The ACC used in the study could be described as an extended conventional CC. It controlled speed according to a target speed decided and set by the driver, but it could also adjust speed in order to keep a safe distance to a leading vehicle. The ACC controlled both the accelerator and the brakes. The driver could manually adjust the target speed up and down in increments of 10 km/h. The ACC system was disengaged either by braking or manually turning it off. If the driver accelerated manually the ACC control would be overridden but the ACC resumed control automatically when the accelerator was released. When a leading car stopped at e.g. a traffic light during ACC driving, the ACC would automatically stop the subject’s car and then start as the vehicle in front started to move - a stop-and-go function.

Figure 2 ACC feedback presentation on the dashboard

ACC feedback was partly integrated in the existing instruments on the dashboard. For instance the speedometer had a circle of amber leds, which were lit to display currently selected target speed. ACC status information was also provided (on/off, leading vehicle detected) (Figure 2). All ACC controls were placed on the direction indicator stalk to the left of the steering column (Figure 3).

Figure 3 ACC controls on the direction indicator stalk

The car body used in the simulator was an ordinary Saab 9000 with an automatic gearbox. The car body of the simulator was 2 meters above floor level. To make it accessible a wheelchair lift was used. If needed, subjects were supported when transferring from the wheelchair to driver's seat. Two types hand controlled accelerator and brakes were used (see Figure 4). The two systems were different both with respect to position and function. With the single lever system the driver braked by pushing and accelerated by pulling the lever (See
2.3 Driving task

The subjects drove on a two-lane, 9 meter wide and 100 km long asphalt road under high friction conditions. Driving was done under daylight conditions with a sight distance of approx. 500 meters. The route included also crossroads with traffic lights. Signed speed limit was in general 90 km/h but 70 km/h at traffic lights. Drivers were instructed to drive, as they would normally do under the same conditions in their own car. The same route was used for all subjects and under both conditions, with and without ACC. The subjects were told that they could turn on and off the ACC system according to their preferences in the ACC condition. Different traffic situations appeared in a randomised, but equal to all subjects, sequence during the driving session. There was oncoming traffic with varying density. Six cross roads with traffic lights where the drivers had to stop appeared along the route. Red squares appearing four times at the left side of the road were used to simulate critical traffic events to which the drivers were instructed to react by pushing the brake control. Four similar but yellow squares were also displayed along the route. The drivers were told not to react to these. The squares were 4 x 4 cm in size and at a distance of 2.5 m from the driver's eyes, representing an approximate sight angle of 1°. The described task was used to measure the drivers’ choice reaction time. Sixteen car-following situations, where the subjects caught up with slower moving vehicles, were included. As the subjects approached the leading vehicles oncoming traffic flow was increased to prevent the subjects from overtaking directly. Catching up was randomly followed by five different types of car-following situations: four lead vehicles braked and then drove off, four drove with varying speed, four drove aside to the right shoulder, and another two cars just drove off after catching up. The fifth situation appeared just before traffic lights. At two occasions the lead cars would stop at the traffic lights, which gave the subjects a chance to use the stop-and-go function during ACC driving conditions.
2.4 Measures
A number of dependent variables like speed, lateral position on the road, time headway, and reaction time were used to analyse performance and behaviour. Other measures like subjective workload and questionnaire responses were used to investigate workload and subjective opinions. The driving simulator's main computer controlled the simulator system at a frequency of 50 Hz while data were recorded at a frequency of 2 Hz. Means were calculated for individual subjects and standard deviation (S.D.) was used as a measure of variation.

The lateral position on the road was measured in relation to a zero position, which was defined as the position where the centre line of the road coincides with the centre line through the driver's body or rather the centre of the steering wheel. Brake reaction time was calculated as the time elapsed from the appearance of a visual stimulus, red square, until the brake lever was depressed with a force of 0.2 N. The resolution was 20 msec. If there was no response from the driver after five seconds it was regarded as miss and the stimulus disappeared. Time headway was calculated as the distance between the front of subject's car and the rear of a leading vehicle divided by the speed of the subject's car. ACC status was also monitored and recorded. Subjective workload was measured with the NASA – RTLX (Raw Task Load Index) rating scale (Byers et al., 1989; Hart & Staveland, 1988). The subjects had to rate the six workload factors: mental demand, physical demand, time pressure, performance, effort and frustration level on a continuous scale ranging from very low to very high (0 - 100). The raw scale version RTLX without pair wise comparison of the six factors was used. Directly after the test all subjects filled in the NASA-RTLX scales for the complete task and the specific situations car following and car following at traffic lights. Questionnaires were used to collect the subject's opinion of driving simulator realism, simulator sickness, speed and distance control, and ACC usage.

3 Results

3.1 Driving behaviour
Group means were calculated and two-way ANOVAs (Analysis of variance) (Keppel, 1991), with repeated measure on the second factor, were used to evaluate the results and the level of significance was set to \( p < .05 \). General driving behaviour was analysed in terms of mean speed and lateral position on the road and the variations (i.e. standard deviation – S.D.) of these measures. Analysis of driving behaviour for the total driving task, 100 km, including car following situations, overtaking and stops at traffic lights did not reveal any significant differences between groups or conditions. Free flow driving, 60% of the route, was defined as those parts of the route where the subjects did not have to deal with catching up, overtaking, or traffic lights but occasionally met oncoming traffic. Free flow driving behaviour was analysed with respect to mean speed, lateral position, and variations in speed and lateral position (Table 2 and 3).
Table 2 Mean speed and speed variation (S.D.) (km/h) for free flow driving (approx. 60 km) for the different experimental conditions

<table>
<thead>
<tr>
<th></th>
<th>Single lever system</th>
<th>Dual lever system</th>
<th>Both</th>
</tr>
</thead>
<tbody>
<tr>
<td>With ACC</td>
<td>95.4 / 3.25</td>
<td>94.1 / 3.27</td>
<td>94.7 / 3.26</td>
</tr>
<tr>
<td>Without ACC</td>
<td>95.0 / 5.33</td>
<td>97.6 / 4.06</td>
<td>96.3 / 4.69</td>
</tr>
<tr>
<td>Both</td>
<td>95.2 / 4.29</td>
<td>95.8 / 3.66</td>
<td></td>
</tr>
</tbody>
</table>

Variation in speed was significantly lower for the ACC condition (Table 4). Other differences were not significant.

Table 3 Mean and variation (S.D.) of later al position (m) for the free flow driving (approx. 60 km) for the different experimental conditions

<table>
<thead>
<tr>
<th></th>
<th>Single lever system</th>
<th>Dual lever system</th>
<th>Both</th>
</tr>
</thead>
<tbody>
<tr>
<td>With ACC</td>
<td>1.52 / 0.29</td>
<td>1.64 / 0.21</td>
<td>1.58 / 0.25</td>
</tr>
<tr>
<td>Without ACC</td>
<td>1.48 / 0.24</td>
<td>1.63 / 0.21</td>
<td>1.55 / 0.23</td>
</tr>
<tr>
<td>Both</td>
<td>1.50 / 0.27</td>
<td>1.64 / 0.21</td>
<td></td>
</tr>
</tbody>
</table>

Drivers using the single lever system drove 14 cm more to the right compared to those using the dual lever system (Table 3) but the difference was not significant (Table 4). The single lever users had a significantly greater variation in lateral position than the other group and the variation for this group was greater with ACC compared to without (Table 3 and 4). The drivers using the dual levers were not influenced by the ACC with respect to variation in lateral position, which caused an interaction between ACC and hand control (Table 4).

Table 4 Results from a two-way ANOVA performed on mean speed, variation (S.D.) in speed, lateral position, and variation (S.D.) in lateral position for free flow driving conditions (approx. 60 km) for the different experimental conditions. (df = degree of freedom)

<table>
<thead>
<tr>
<th>Factor</th>
<th>Source</th>
<th>df</th>
<th>F</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed variation</td>
<td>ACC</td>
<td>1,18</td>
<td>19.79</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Variation in lateral position</td>
<td>ACC</td>
<td>1,18</td>
<td>8.266</td>
<td>0.010</td>
</tr>
<tr>
<td></td>
<td>Hand control</td>
<td>1,18</td>
<td>6.765</td>
<td>0.018</td>
</tr>
<tr>
<td></td>
<td>ACC * Hand control</td>
<td>1,18</td>
<td>8.266</td>
<td>0.010</td>
</tr>
</tbody>
</table>

Variation in speed (km/h) during free flow driving was analysed to detect possible degradation in manual speed keeping performance compared to ACC driving. The difference in speed variation between no ACC and ACC condition increased with distance driven.
(Figure 5). There was a significant \[ F(1,18) = 5.093, p=.037 \] linear trend but the seemingly difference between hand controls was not significant.

![Figure 5 Differences in speed variation (km) between ACC and No ACC conditions per distance driven.](image)

3.2 Choice reaction time
Mean reaction times were calculated for the two conditions with ACC and without ACC for all subjects (Figure 6). The average reaction times were shorter for the ACC condition and for the dual lever drivers but these differences were not significant. The reaction times were also analysed for both groups with respect to order of presentation, but no statistically significant effects were revealed either due to order of presentation or ACC mode.

![Figure 6 Mean reaction time (s) for the different experimental conditions](image)
3.3 Car following

The car following situations were analysed with respect to mean headway, variation in headway and shortest headway. Time headway was calculated as the distance between the front of the subject’s car and the rear of the car in front divided by the subject’s speed. The catching up procedure was the same for all situations but they ended differently as previously described. Fourteen car following situations were included in the analysis. The two car following situations at traffic lights were disregarded as they were considered to be different in character. Mean headway was significantly longer, [F(1,18)= 9.234, p=.007] for the unsupported condition compared to ACC driving (Table 5). Furthermore, variation in headway was significantly reduced when the ACC system was available [F(1,18)= 16.273, p=.001]. There were no significant main effects with respect to hand control and no interactions.

Table 5 Mean and variation (S.D.) in time headway (s) over 14 car following situations for the different experimental conditions

<table>
<thead>
<tr>
<th></th>
<th>Single lever system</th>
<th>Dual lever system</th>
<th>Both</th>
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</thead>
<tbody>
<tr>
<td>With ACC</td>
<td>2.56 / 1.03</td>
<td>2.61 / 1.05</td>
<td>2.59 / 1.04</td>
</tr>
<tr>
<td>Without ACC</td>
<td>3.19 / 1.40</td>
<td>3.42 / 1.30</td>
<td>3.31 / 1.18</td>
</tr>
<tr>
<td>Both</td>
<td>3.02 / 1.22</td>
<td>2.88 / 1.18</td>
<td></td>
</tr>
</tbody>
</table>

The shortest time headways were considered to be critical for the car following situations. Mean of shortest headways for both groups of subjects was prolonged when the ACC was used, 1.26 s as compared to 1.08 s. However, the individual differences were great and differences between conditions were not significant. Analysis of speed and lateral position for the car following situations showed that variation in speed decreased with 10% and variation lateral position increased by 12% when the ACC was available (Table 6). Single lever drivers drove on average more to the right with the ACC available while the other group showed a reversed pattern, which resulted in a significant interaction [F(1,18)= 6.428, p=.021]. Other differences were not significant.

Table 6 Results from a two-way ANOVA performed on speed and lateral position measures for the car following situations (df = degree of freedom)

<table>
<thead>
<tr>
<th>Factor</th>
<th>Source</th>
<th>df</th>
<th>F</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed variation</td>
<td>ACC</td>
<td>1,18</td>
<td>22.025</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Lateral position</td>
<td>ACC * Hand control</td>
<td>1,18</td>
<td>6.428</td>
<td>0.021</td>
</tr>
<tr>
<td>Variation in lateral position</td>
<td>ACC</td>
<td>1,18</td>
<td>8.094</td>
<td>0.011</td>
</tr>
</tbody>
</table>
3.4 Workload

The subjects rated their workload for the total driving task, car following situations, and car following at traffic lights using the NASA - RTLX scale. The loading factors were in general rated lower and performance higher when driving with ACC (Figure 7) for both groups. The ACC system was engaged over 97% of the driving time for both groups.

![Figure 7 Mean workload ratings for both groups (n=20) of the total driving task with and without ACC.](image)

Five of the differences shown in Figure 7 were significant: mental demand \([F(1,18)= 7.618, p=.018]\), physical demand \([F(1,18)= 11.759, p=.003]\), time pressure \([F(1,18)= 7.044, p=.016]\), performance \([F(1,18)= 8.455, p=.009]\), and effort \([F(1,18)= 4.584, p=.046]\). There were no significant differences between hand control used and no interactions were found.

The 16 car following situations were also considered to be substantially less loading under ACC driving conditions, e.g. 70% decrease in physical demand. The differences between ACC conditions were significant for all of the workload factors (Table 7). There was also a significant difference between the two experimental groups for mental demand, i.e. 21 (single) vs. 37 (dual). Apart from this, there were no significant differences between single and dual lever drivers. No interactions were found.
Table 7 Results from a two-way ANOVA performed on the six workload factors of NASA-RTLX for the car following situations (df = degree of freedom)

<table>
<thead>
<tr>
<th>Factor</th>
<th>Source</th>
<th>df</th>
<th>F</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mental demand</td>
<td>ACC</td>
<td>1,18</td>
<td>14.510</td>
<td>0.001</td>
</tr>
<tr>
<td>Physical demand</td>
<td>ACC</td>
<td>1,18</td>
<td>24.636</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Performance</td>
<td>ACC</td>
<td>1,18</td>
<td>12.895</td>
<td>0.002</td>
</tr>
<tr>
<td>Effort</td>
<td>ACC</td>
<td>1,18</td>
<td>7.556</td>
<td>0.013</td>
</tr>
<tr>
<td>Frustration</td>
<td>ACC</td>
<td>1,18</td>
<td>9.466</td>
<td>0.007</td>
</tr>
</tbody>
</table>

Workload was also assessed for the two car following situations at traffic lights. ACC driving condition for these situations meant that the subjects used the stop-and-go function of the ACC. Only one driver disengaged the ACC, and this was done by mistake. Workload was rated significantly lower for the ACC condition, i.e. all loading factors were significantly lower and performance was higher (Table 8). Also here it was found that drivers using the dual lever system found the situation more mentally loading.

Table 8 Results from a two-way ANOVA performed on the six workload factors of NASA-RTLX for the car following situations at traffic lights (df = degree of freedom)

<table>
<thead>
<tr>
<th>Factor</th>
<th>Source</th>
<th>df</th>
<th>F</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mental demand</td>
<td>ACC</td>
<td>1,18</td>
<td>21.758</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Mental demand</td>
<td>Hand control</td>
<td>1,18</td>
<td>6.225</td>
<td>0.023</td>
</tr>
<tr>
<td>Physical demand</td>
<td>ACC</td>
<td>1,18</td>
<td>22.844</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Time pressure</td>
<td>ACC</td>
<td>1,18</td>
<td>12.412</td>
<td>0.002</td>
</tr>
<tr>
<td>Performance</td>
<td>ACC</td>
<td>1,18</td>
<td>9.133</td>
<td>0.007</td>
</tr>
<tr>
<td>Effort</td>
<td>ACC</td>
<td>1,18</td>
<td>9.292</td>
<td>0.007</td>
</tr>
<tr>
<td>Frustration</td>
<td>ACC</td>
<td>1,18</td>
<td>6.604</td>
<td>0.019</td>
</tr>
</tbody>
</table>

3.5 Driver opinions
The subjects were asked how well they thought they could control speed and distance to lead vehicles during following situations and how much effort they allocated. Answers were given on 7-point discrete scales. Speed and distance performance was rated higher under ACC conditions and the allocated effort as lower (Table 9).
Table 9 Mean subjective estimations of speed and distance keeping performance and effort for the different experimental conditions

<table>
<thead>
<tr>
<th>Aspect</th>
<th>Hand control</th>
<th>ACC</th>
<th>No ACC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed keeping</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>very bad (1)</strong></td>
<td>Single</td>
<td>6.2</td>
<td>3.5</td>
</tr>
<tr>
<td><strong>to</strong></td>
<td></td>
<td>6.2</td>
<td>4.5</td>
</tr>
<tr>
<td><strong>very well (7)</strong></td>
<td>Dual</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Speed effort</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>non (1)</strong></td>
<td>Single</td>
<td>1.5</td>
<td>3.9</td>
</tr>
<tr>
<td><strong>to</strong></td>
<td>Dual</td>
<td>1.6</td>
<td>3.3</td>
</tr>
<tr>
<td><strong>very high (7)</strong></td>
<td>Both</td>
<td>1.6</td>
<td>3.6</td>
</tr>
<tr>
<td>Distance keeping</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>very bad (1)</strong></td>
<td>Single</td>
<td>5.7</td>
<td>4.6</td>
</tr>
<tr>
<td><strong>to</strong></td>
<td>Dual</td>
<td>5.9</td>
<td>4.6</td>
</tr>
<tr>
<td><strong>very well (7)</strong></td>
<td>Both</td>
<td>5.8</td>
<td>4.6</td>
</tr>
<tr>
<td>Distance effort</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>non (1)</strong></td>
<td>Single</td>
<td>1.9</td>
<td>3.1</td>
</tr>
<tr>
<td><strong>to</strong></td>
<td>Dual</td>
<td>1.5</td>
<td>2.8</td>
</tr>
<tr>
<td><strong>very high (7)</strong></td>
<td>Both</td>
<td>1.7</td>
<td>3.0</td>
</tr>
</tbody>
</table>

All differences were found to be significant: speed control \(F(1,18)= 27.140, p<.001\), speed effort \(F(1,18)=19.776, p<.001\), distance control \(F(1,18)=5.959, p=.025\), and distance effort \(F(1,18)=17.744, p=.001\). There were no significant effects due to type of hand control used. After driving with the ACC the subjects were asked rate some aspects, which were considered to be important for ACC usage and acceptance (Table 10). The results showed that they rated the ACC system very high, all means were over 6 on a 7-point scale.

Table 10 Mean subjective ratings for some aspects of the ACC system for all subjects (n = 20)

<table>
<thead>
<tr>
<th>Aspect</th>
<th>Mean</th>
<th>S.D.</th>
<th>Rating scales</th>
</tr>
</thead>
<tbody>
<tr>
<td>General opinion of the ACC?</td>
<td>6.7</td>
<td>0.75</td>
<td>very negative (1)</td>
</tr>
<tr>
<td>ACC contribution to comfort?</td>
<td>6.5</td>
<td>0.95</td>
<td>very negative (1)</td>
</tr>
<tr>
<td>Learning to use ACC?</td>
<td>6.7</td>
<td>0.59</td>
<td>very difficult (1)</td>
</tr>
<tr>
<td>Trusting ACC?</td>
<td>6.5</td>
<td>0.69</td>
<td>very easy (7)</td>
</tr>
<tr>
<td>Wishing to have ACC?</td>
<td>6.9</td>
<td>0.45</td>
<td>not at all (1)</td>
</tr>
<tr>
<td>ACC better than own CC?</td>
<td>6.5</td>
<td>0.77</td>
<td>much worse (1)</td>
</tr>
</tbody>
</table>

The subjects were asked to estimate where they placed their right hand when the ACC was engaged. The driver's right hand is normally used for the accelerator and brake control. Single lever users drove with both hands on the steering wheel only 28% of the time compared to
48% for the other group. Almost all subjects, 95 %, had a CC in their own car. They used it frequently and rated the usefulness as very high. Finally, the subjects were asked to rate the experienced realism in the simulator on a seven-point scale ranging from 1 (not at all realistic) to 7 (very realistic). The mean rating for the ACC condition was 5.3 and for the no ACC condition 5.0. The difference was not significant.

4 Discussion

The purpose of this study was twofold. The first purpose was to evaluate specific adaptations, the ACC and the two types of hand controls, and the second was to contribute to the development of general method to evaluate vehicle adaptations. The current evaluation included aspects like usability, safety, workload, and acceptance.

4.1 Usability and safety

Driver behaviour was analysed in order to evaluate the usability aspects. The driver should be able to use the adaptation, as intended, and it should have a positive or, at least, not a negative effect on driving behaviour. The evaluation has to consider safety in order to reveal possible negative effects. Safety in this context is limited to active safety, i.e. the driver’s ability to control the vehicle in a way that crashes and incidents are avoided. Passive safety, i.e. possible consequences of a crash was not considered here.

Driving behaviour was analysed with respect to speed, lateral and longitudinal control. There were no significant effects of ACC or type of hand control on the average speed for free flow driving but the speed was approx. 5 km/h above signed speed (Table 2). This corresponds rather well to how Swedish drivers actually drive. The variation in speed during free flow driving was significantly reduced when the ACC was in use (Table 2 and 4). This implies a softer and thus a safer driving behaviour with possible positive environmental effects for both hand controls.

Steering control was analysed by investigating the lateral position of the vehicle. It was found that the variation in lateral position was less when the ACC was not available (Table 3). However, this difference was only found for the group using the single lever system. The other group was not influenced by ACC usage and had a consistently lower level of variation. Approximately the same was found for the car following situations; ACC usage increased the variation in lateral position and the single lever drivers varied more than the other group (Table 6).

It was expected to find differences among the four conditions. First of all, a cruise controller could improve lateral control for driver using hand controls as both hands could be used for steering. Furthermore, in an earlier simulator study (Peters, 2001) with quadriplegic drivers it was found that the variation in lateral position was greater for the drivers who used the dual lever system compared to single lever users. It was suggested that this could have been a result of an interaction between the steering and speed keeping control. The current findings do not correspond to the expectations but there are several possible explanations. First of all, subjects participating in this study had full function in their upper limbs while the quadriplegic drivers in the previous study were impaired in their upper limbs. Furthermore, the current driving task was less demanding with respect to steering control compared to the other. The single lever users steered with one hand more than 70% of the time even when the ACC was available and they could have used both hands. This supports the assumption that
the driving task was not demanding enough to reveal the potential effects of ACC on steering control. One possible explanation for the increase in variation for the ACC condition could be that driving became more relaxed, less loading. Nilsson (Nilsson & Nåbo, 1995) found a tendency that variation in lateral position decreased as task load increased, telephoning while driving. The observed differences, even though significant, were small (2 – 3 cm for ACC and 4 – 6 cm for hand control condition) and even if the single lever drivers had a greater variation in lateral position, they were still well within the lane. In summary, the results do not suggest that there were any relevant differences in safety between the conditions.

Car following situations require the driver to control both speed and distance to leading vehicles. These are situations where the ACC can provide support but not a conventional CC. The analysis of time headway showed that both variations in headway and mean headway decreased by 0.7 seconds when the ACC was available. This means that on average were the subjects driving 17 m closer at a speed of 90 km/h to the vehicle in front. The decrease in variation is probably a clear positive effect of ACC usage. However, the shorter distance was accepted but it does not seem to conform to the distances found under the unsupported condition. Comments were also made that the ACC used a too short headway. Nilsson & Nåbo (Nilsson & Nåbo, 1995) found that the shortest headways were reduced under ACC supported condition. Even if some of the shortest headways were eliminated also in this study the average of the shortest headways was not significantly different with respect to ACC condition. The results indicate that it is important that headway can be individually adjustable according to driver's characteristics and preferences within a certain range. The need of adjustable headway is likely to be even more pronounced in bad weather conditions, night-time driving etc.

When the ACC system was engaged the driver could place his/her right hand on the steering wheel or on the brake lever or somewhere else irrelevant to the primary driving task. If the driver chose to place it on the brake lever this could influence the brake reaction time. Single lever drivers estimated that they on average had the right hand half of the time on the brake and the dual lever drivers one third of the time. However, there was no influence of ACC mode or type of hand control on brake reaction times. The same result was found for able-bodied drivers (Nilsson & Nåbo, 1995).

In summary it was found that the ACC in combination with both hand controls was usable and had no negative effect on traffic safety and there were no substantial differences between the hand controls. However, it seems like the ACC used too short time headway criterion compared to what they use when free to choose. This was a reversed result compared to what Nilsson and Nåbo (Nilsson & Nåbo, 1995) found for able-bodied drivers.

4.2 Workload

Driving with hand controls often impose a high load on the driver's upper limbs. Both hands are continuously occupied with the primary driving task. This often cause strain and discomfort and could reduce active safety but most frequently it will result in reduced mobility and independence, e.g. driving less frequently and shorter distances. The ACC system was evaluated to find out if it could reduce the load on the driver. Workload was measured with NASA - RTLX rating scales. It was found that ACC supported driving was experienced to be substantially less loading, especially physical demand and effort, and performance was better (Figure 7). This result was even more pronounced for the car following situations including the situations at traffic lights (Table 7 and 8). The levels found
for the unsupported condition were in good correspondence to what was found in the earlier cited study with quadriplegic drivers (Peters, 2001), while the workload level for the ACC condition was approximately equal to what was found for able-bodied drivers using ACC (Nilsson & Nåbo, 1995). However, the ACC support did not influence the workload level for able-bodied drivers. Specific questions on speed and distance control showed that the subjects found it easier and required less effort to control both speed and distance to leading vehicles with the ACC system available (Table 9). Difference in speed variation increased with driven distance (see Figure 5), which also supports the conclusion that ACC reduced workload. In summary it was found that experienced workload decreased substantially when the ACC support was available for both driver groups.

4.3 Driver opinion

The drivers participating in this study had extensive experience of conventional cruise controllers as 95% had a CC in their own car. This percentage is high even among drivers of adapted cars. A recent survey among drivers of adapted car showed that about 40% of their cars had a CC installed (Henriksson, 2001). The ACC system, including the stop-and-go function, was very well accepted, considered easy to learn, wanted and trusted by the subjects (Table 10). The ACC was also very much preferred over conventional CCs. Thus it seems very likely that the ACC application will be very well received by drivers who drive with hand controlled accelerator and brakes.

5 Conclusions

In conclusion it was found that the ACC application served its purpose well independent of what hand control system the driver used. The applied evaluation method seems to be useful, however, not comprehensive. There is a need to further develop e.g. principles of how to design the driving task in relation to the evaluation objectives. Maybe the current driving task was not demanding enough to reveal potential risks. Furthermore there is a need to elaborate the evaluation parameters and criteria. Steering, speed and distance control are critical parameters but the way to measure and interpret the results needs to be refined. Finally, the ACC application can from the users point of view be seen as consisting of three parts: the function provided by the ACC, the input or control of the ACC and the output or feedback from the ACC. The current evaluation method does not explicitly include the in- and output aspects of the ACC device. A comprehensive evaluation should also include these aspects.

References


Elderly and Disabled Travellers: ITS Designed for the 3rd Millenium

1 Published in Transportation Human Factors 1(2), 1999. The article was commented by Campbell (1999) and a reply to the comments (Nicolle & Peters, 1999a) was included in the same issue. Reprint permission has been granted.
Elderly and Disabled Travellers: ITS Designed for the 3rd Millenium

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Loughborough University*

Björn Peters  
*Swedish National Road and Transport Research Institute (VTI)  
and HMI Graduate School  
Linköping University*

The TELematic Standards and Coordination of Advanced Transport Telematics systems in relation to elderly and disabled travelers (TELSCAN) project in the Transport Sector of the Telematics Applications Programme of the European Union has developed a *Handbook of Design Guidelines* (Nicolle & Burnett, 1999) to support designers of Intelligent Transport Systems (ITS) to include the needs of people who are elderly or disabled. This paper describes the methods of the *Handbook’s* development, including an overview of the methodology for capturing the requirements of elderly and disabled travelers, a survey of existing guidelines, and empirical results and lessons learned from simulator testing. The authors conclude that although general guidelines are necessary, the most specific and useful guidelines emerge only when carefully chosen research questions can be investigated. The development of such guidelines should help us come closer to achieving usability of ITS not only for elderly and disabled people, but for everybody as we enter the 3rd millennium.

The main objective of Intelligent Transport Systems (ITS), also known as Advanced Transport Telematics (ATT), is to increase safety and efficiency in transport, whether it be on the road, rail, sea or in the air. However, some persons may experience difficulties in both their performance of the traveling task and the use of new technology. This may be due to a decline in motor performance, reaction times, vision, hearing, or information processing ability, caused by either the normal process of ageing or perhaps through disease or an accident. Some ITS may provide information to the traveler, some may provide warnings in hazardous conditions, and some may assist a driver in controlling the vehicle. Emergency call systems and route guidance and navigation systems may increase safety and restore confidence for elderly or disabled drivers, provided that the controls and displays are designed with their special requirements in mind. If this is the case, elderly and disabled people need not be ‘handicapped’ by their impairments. This can best be illustrated by referring to definitions from the World Health Organisation (1980/1993):
• **Impairment**: Any loss or abnormality of psychological, physiological or anatomical structure or function, i.e., parts or systems of the body that do not work (p. 47).

• **Disability**: Any restriction or lack (resulting from an impairment) of ability to perform an activity in the manner or within the range considered normal for a human being, for example, unable to see clearly, to walk unaided, or to hear (p. 143).

• **Handicap**: A disadvantage for a given individual, resulting from an impairment or a disability, that limits or prevents the fulfillment of a role that is normal (depending on age, sex and social cultural factors) for that person (p. 183).

It could therefore follow that a handicap is the result of a mismatch between the user’s needs and abilities and the ITS environment. It would then be possible to have an impairment and a disability but no handicap: a person who uses a wheelchair may not be handicapped if the environment has been designed to take account of wheelchair users, for example through the use of ‘curb-cuts’ to allow easy access from sidewalk to street.

With regard to new technology, elderly and disabled travelers may be the most likely to benefit, but in reality may have difficulties in taking advantage of the system due to the very same limitations. Thus, as vehicles get faster, our roads busier, and the able-bodied traveler seemingly more efficient, elderly or disabled travelers may find themselves lagging further behind and with potentially increased safety risks -- unless ITS are designed with their functional impairments and their requirements in mind. So, just as everybody loves a ‘curb-cut’, like the mother with a stroller or the child on a skateboard, it is not just the disabled or elderly traveler who will benefit from better guidelines for ITS.

**BACKGROUND RESEARCH ON ELDERLY AND DISABLED TRAVELERS**

The Telematic Applications for the Integration of Drivers with Special Needs (TELAID) project was part of the European DRIVE II Programme and ran from 1992 to 1995. TELAID systematically investigated the requirements of people with disabilities who need the use of car adaptations whilst driving (Naniopoulos and Bekiaris, 1995). The DRIVE II Elderly and Disabled Drivers Information Telematics (EDDIT) project concentrated on the elderly driver, using conventional controls but with a normal, gradual deterioration in perceptual and performance abilities. This article is based on the research from TELAID, which joined with EDDIT to form the current Telematic Standards and Coordination of ATT systems in relation to elderly and disabled travelers (TELSCAN) project in 1996. Part of the Transport Sector of the 4th Framework Telematics Applications Programme of the European Union, TELSCAN broadened the research to include the needs of elderly and disabled drivers and travelers in the development and application of ITS, whether it be as drivers using their own cars, or as travelers in various modes of public transport (Naniopoulos and Bekiaris, 1997). So the earlier research for this paper centers on the driver, and then is extended to the needs of travelers using all forms of transport.

Although the use of public transport is promoted as more environmentally friendly, a private car is still the most common form of travel, providing a level of freedom and independent mobility for people with impairments that public transportation does not offer. Access to private cars can bring a new dimension to the lives of disabled and elderly people, who may otherwise have lost, or are starting to lose, their mobility.
In Europe, figures for the number of elderly and disabled drivers vary widely depending on the country’s definition of disability. Over the next 20-30 years, it is fair to say that elderly people, over 65 years, will represent more than 20% of the total European population, and many of these people will have some form of disability. However, elderly people do not form a homogeneous group, and many elderly people have active and healthy lives, even though the natural process of ageing has reduced certain abilities. Chronological age is not a true indicator of deterred performance and increased disabilities, and variability also increases with age (see e.g., Hakamies-Blomqvist, 1996; Waller, 1991). Therefore, where this paper uses the terms elderly and disabled, we do not imply that elderly people are disabled. It is also important to stress that any available figures cannot necessarily indicate the number of people who would benefit from better design of ITS. To illustrate, if elderly drivers do not want a collision avoidance system to take control of their driving, then a well-designed interface will not convince them to buy it. It is, therefore, very important to investigate the likelihood of people actually using or wanting to use a system. This kind of information is not easily available and requires further study, including intensive cost/benefit analyses.

People with disabilities do not want vehicles designed specifically for them, which would emphasize their disabilities. Instead most would prefer existing systems that can be adapted to their requirements -- a ‘design for all’ or universal design which does not exclude them from using the system. Everyone has the right to enjoy using a system, which suits his/her needs and aspirations. Designing for the least able also usually ensures that the device is easier and more convenient for everyone to use (Waller, 1991).

Although, in principle, many product designers and developers wish to consider the needs of elderly and disabled people, they may find it difficult to know where to begin, which groups to include, how to include them and how to ensure that all the users’ main problems and concerns are covered. TELSCAN has developed a Handbook of Design Guidelines (Nicolle & Burnett, 1999) promoting the “design-for-all” concept, which can assist in this process.

THE TELSCAN GUIDELINES HANDBOOK - A WORKING DRAFT

TELSCAN’s Handbook (Nicolle and Burnett, 1998) proposes guidelines for designing systems so that they are easier and safer to use by elderly and disabled drivers and travelers. It is a living, working document on the World Wide Web, and more specific guidelines are being added as TELSCAN conducts collaborative testing with other projects, as well as literature and project searches for further guidelines.

The Handbook emphasizes that driving is just one aspect of the total traveling chain, and in order for an elderly person or a person with a disability to travel, each link in that chain must meet the users’ requirements. For example, a multi-modal trip planning system ought to contain relevant information for the traveler with a disability to park his/her car at the train station, know ahead of time if there are any delays, and if the destination station has any stairs or long distances to cover. Currently the Handbook consists of the following sections, each level becoming more relevant to specific systems:

- Usability principles applicable to all ITS
- General guidelines for all ITS and their facilitating technologies (e.g., controls, displays, smart cards, the Internet, etc.)
• Guidelines for varying contexts of use (e.g., kiosks for the traveller or systems for drivers, whether inside or outside the car)
• Guidelines for specific systems and system functions

METHODOLOGY TOWARDS DEVELOPMENT OF DESIGN GUIDELINES FOR ITS

The guidelines have evolved through a number of activities, starting during TELAID and continuing in the TELSCAN project:

• Survey of existing guidelines which may be relevant to vehicles and ITS, including those developed for computer accessibility by people with disabilities.
• Identification of requirements of elderly travelers and travelers with disabilities.
• Identification of design issues which then need to be considered in the design of ITS.
• Simulator tests and field trials, either as the project’s own empirical testing or in co-operation with other transport telematics projects.

Survey of Guidelines

Many existing guidelines were developed with a view to be used for traditional computer applications in offices and may not readily apply to the complexity of the driving task or to a changing environment whilst driving (e.g., Nordic Cooperation on Disability, 1998). Furthermore, various guidelines may either be conflicting or may be too general to provide the advice needed by designers. To illustrate, recommended minimum text sizes for visual displays may range from 0.3° to 0.6° visual angle, corresponding to a character size of 3 to 6 mm viewed from 60 cm (Suen, Mitchell, and Henderson, 1998). A more general guideline for in-vehicle displays suggests that the size of the characters must be large enough and the contrast high enough so that the driver does not need to bend toward the display to read the information (Graham and Mitchell, 1997; Nicolle and Burnett, 1998). This guideline, even though emerging from in-vehicle testing, leaves interpretation to the designers themselves.

Many other available guidelines, drawn from sectors such as telecommunications or from good human factors in general, have simply been based on expert opinion and intuition, and not on experimental evidence. Therefore, reliable data is often missing which could provide more specific design advice.

Some guidelines for the design of ITS exist already (Campbell, Carney, and Kantowitz, 1998; Green, Levison, Paelke, and Serafin, 1995; Ross, et al., 1996) and others are under development, for example, within transport telematics research projects like TELSCAN. Although these guidelines may consider the general needs of older drivers, they do not always address the needs of people with disabilities, often due to the difficulty of making specific recommendations for such diverse user requirements.

The DRIVE II Harmonization of ATT Roadside and Driver Information in Europe (HARDIE) project developed guidelines for the presentation of information in navigation and route guidance systems, travel and traffic information systems, collision avoidance, Autonomous Intelligent Cruise Control, and Variable Message Signs (Ross et al., 1996). Although the needs of elderly people and people with disabilities were considered in a general sense, these user groups were not specifically included in the testing. In contrast, Green et al. (1995) conducted a road-based study that aimed to establish the optimum timing of voice-based route guidance messages and included driver age as an independent variable. It was found that older drivers required guidance messages to be presented significantly
further back from a decision point, as compared with younger drivers. These studies are being used as a basis for some of TELSCAN’s recommendations, but more similar work is needed in this area.

**Identification of User Requirements**

The TELAID project identified the requirements of drivers with different types of impairments. The study involved interviews with 56 experts and some 50 interviews and observations of drivers with special needs across seven European countries (covering visual impairments, reading, hearing, speech, lower limb, upper limb, upper and lower limb, upper body, sudden loss of control and cognitive impairments).

A definition of the *driving task* was used as a series of prompts during the interview process. This driving task definition covered not just safely controlling the vehicle, but also actions like ingress and egress, which could determine whether the person was able to drive or not. This data collection was then extended during the TELSCAN project to include the requirements of elderly and disabled travelers using different modes of transport, including private cars (integrating the results of TELAID and EDDIT), buses/trams, metros/trains, ships and airplanes. The specification of users’ requirements (Nicolle, Ross, and Richardson, 1993; Nicolle, Veenbaas, and Ross, 1997) suggested many design issues that need to be investigated further, either through empirical testing, discussions with experts, or comparative studies of existing guidelines.

**Identification of Design Issues**

The users’ requirements stressed that a driver must be able to choose the most appropriate input or output mode to meet any special needs. The visual channel, for example, must not become overloaded for people with hearing impairments. The tendency to use synthetic voice and other acoustic output might lead to some people *becoming* drivers with special needs if they are not able to hear a message or warning from the system.

Design guidelines for in-vehicle information systems state that route information should be given sufficiently in advance of the maneuver for it to be accomplished safely (e.g., Southall & Robertson, 1994). However, some users, particularly a disabled or elderly person, may require earlier messages to compensate for slower reaction times (Green et al., 1995).

Response times need to be investigated for various systems and with all possible users. For example, a value of 4 seconds for time-to-collision is recommended for collision avoidance systems (Nilsson, Alm, and Janssen, 1992). An older or disabled driver might require earlier warning or information presentation. Older drivers, whose speed of perceptual and cognitive processing slows down, would also benefit if the display time of messages on the screen could be increased, or if alert messages could remain on the screen until they are dismissed by the user.

An area that needs to be investigated is the glance time necessary to obtain information from an in-vehicle display. Guidelines exist for the number and duration of glances that an able-bodied driver needs to obtain a specific chunk of information. Zwalen, Adams, and Debald (1988) indicated that visual information on displays should be designed so that not more than three consecutive glances of average duration 1 second are needed to obtain the information, and that glances in excess of 2 seconds are unacceptable. Older
people are likely to take a longer time to deal with visual information and to perform a task (Hakamies-Blomqvist, 1996). Furthermore, the more complex the information presented on the screen, the greater the number of errors made, especially by older drivers (Graham and Mitchell, 1997). To help alleviate the problems of excessive glance duration and complex visual displays, Graham and Mitchell (1997) suggest a break between screens in a message pair to enable drivers to reorient themselves to the road ahead. This is good human factors, but even more crucial for the older or disabled driver.

Above all, the users’ requirements identified that the control aspects of the driving task can be crucial for people with disabilities, sometimes stopping them from even setting out on a journey. Drivers with severe lower limb disorders have to rely on their upper limbs in order to drive a car. Both steering and speed-keeping require continuous control of the steering wheel and the accelerator, causing static and sometimes uncomfortable postures which have to be maintained over long periods. A driver who must use hand controls for the primary (steering, braking) and secondary (lights, directional signals) driving tasks may find that additional control tasks either prove difficult or could have serious safety implications.

The survey identified long distance driving as a particular problem for many drivers with disabilities. It was decided to investigate this issue further, firstly, how the driving performance of people with lower limb impairments compared with that of able-bodied drivers, and secondly, what effect telematics might have on workload and performance for the driver with disabilities.

Investigating Workload and Performance Without Telematics

Hand control systems for drivers with lower limb impairments can be implemented in different ways. Figure 1 illustrates three types of controls: a ring accelerator, a segment accelerator, and a manually operated brake (Veenbaas and Hekstra, 1993). Only one of these hand-controlled accelerators would be present at any one time. With a ring accelerator, the acceleration pedal is replaced by an acceleration ring of smaller radius, mounted on top of the steering wheel and operated by the thumbs or palms of the hands. This enables the driver to steer with both hands and operate switches on either side of the steering column. With a segment accelerator, the acceleration pedal is mechanically connected to a curved lever, as seen to the right of the steering wheel. The brake pedal is connected to an additional lever, as shown to the right of the segment accelerator.

Alternatively, Figure 2a shows a single combined lever for accelerator and brake mounted on the floor between the front seats. This single lever could instead be placed to the side of the steering wheel. Figure 2b shows another system consisting of two separate levers for accelerator and brake placed on the right side of the steering wheel column (Peters, 1996).
Two important aspects of hand control systems are positions of the control/s and if there are combined or separate controls for brake and accelerator. Physical discomfort and fatigue are common problems (Peters and Nilsson, 1993; Verwey, 1995). Because of a lower limb impairment, drivers using particular car adaptations (e.g., a hand-controlled segment accelerator) find it difficult to accelerate or brake at the same time as using another control, and ring accelerators are preferred over segment accelerators. This applies to drivers with disabilities driving with or without telematic systems because of the discomfort associated with the segment accelerator (Verwey, 1995).
Peters and Nilsson (1993) conducted a driving simulator study in order to investigate the driving performance of people with lower limb impairments compared with that of able-bodied drivers. The study was conducted with drivers with quadriplegia (paralysed lower limbs and trunk and impaired mobility and strength in upper limbs), using the two types of hand controls in Figure 2. The moving base driving simulator at the Swedish Road and Transport Research Institute (VTI) was used for the testing (see Figure 3).

Figure 3 Using the elevator lift to enable people in wheelchairs to enter the dynamic simulator at the Swedish Road and Transport Research Institute.

Twenty-six drivers with quadriplegia were compared with a group of able-bodied drivers, matched in age, gender and experience. All participants drove an 80 km long route on a rural road with signed speed of 90 km/h. The drivers with quadriplegia drove with the same kind of hand controls as they had in their own cars. There were no significant (5%) differences in speed control between the driver groups. However, using NASA Raw Task Index (NASA-RTLX) to measure their subjective workload (Byers, Bittner, and Hill, 1989), the drivers with quadriplegia experienced a heavier time pressure compared to the able-bodied control group. Drivers with quadriplegia, and even more so those using the single lever hand control, also thought it was physically more tiring to brake and accelerate compared to the able-bodied participants. As a measure of the drivers’ lateral control, the mean variation in lateral position was calculated over all straight sections of the route for each participant. There was no significant difference between the drivers with quadriplegia and the control group. However, drivers using the dual lever system mounted on the steering wheel column had greater variation in lateral position. This could have been caused by interference between steering and speed control. It was also found that drivers with quadriplegia driving with hand controls had a 10% longer brake reaction time (group average 0.90 sec) compared to able-bodied drivers using a foot brake.
In summary, it was found that drivers with quadriplegia using hand controls largely compensate for their disability, but they do it at a cost of physical tiredness and high workload. The longer reaction time also indicates that the design of the hand controls was not optimal and did not fully compensate for their disabilities.

Could in-car ITS help to alleviate these driving control fatigue problems?

**Adaptive cruise controller (ACC) - a step in the right direction?** Cruise Controls (CCs), which keep a constant speed set by the driver, have been available as options in many cars for 15 to 20 years. The CC is often considered to contribute to comfort for the average driver, but it is also a crucial support system for many drivers with lower limb impairments, allowing them to decrease load on the upper limbs. However, CC is only useful on highways with no or low traffic density.

The ACC is an improved CC that can adapt speed to preceding slower vehicles without driver intervention. This is achieved by linking the cruise controller with a sensor in the front of the vehicle that can detect forward moving obstacles. Speed is then adapted to keep safe distance to a leading vehicle. This extended functionality of the ACC could be of great help even on short journeys for drivers with lower limb disabilities.

Driving with ACC can influence driving behavior in many ways both positive and negative. In a driving simulator study, Nilsson and Nåbo (1996) found that ACCs improved driving performance during car-following situations. Speed and headway variabilities were reduced and the shortest headways were decreased. However, another driving simulator study (Nilsson, 1996) revealed some negative effects in critical traffic situations. ACC drivers had more collisions than unsupported drivers when approaching a stationary queue. This result was explained by too high expectations on the ACC system. There is a risk that the driver might expect the ACC to function also as a Collision Avoidance System. Thus, it is very important to make this distinction clear to the user and this should be reflected in the interface design of the ACC. Feedback must be designed so that the driver is able to hear, see, or feel the information, whatever disabilities he/she may have.

The issues above formed important considerations in the design of the testing conducted in the TELAID project. It was anticipated that this testing could then be used to formulate some specific design guidelines to help bring the system closer towards a ‘design for all.’

**Driving Simulator Test -- Introducing ITS**

A driving simulator study was performed to evaluate an ACC system with drivers with lower limb disabilities, or paraplegia (Peters, 1996). The purpose of this experiment was to investigate how ACC driving contributes to improving the driving conditions for drivers with lower limb disabilities. Another consideration was to investigate whether ACC had a different influence depending on the type of hand control system the driver used for accelerating and braking.

Twenty experienced drivers with lower limb disabilities participated in this experiment. All participants had full strength and mobility in their upper limbs. The subjects were divided into two groups depending on the type of hand control they used, single or dual lever system. All participants drove with the same type of hand controls they had in their
own cars. The types of hand controls used were the same as in the previous experiment (Figure 2).

The driving simulator at VTI was equipped with an ACC. The ACC controlled both throttle and brakes and could adapt speed in order to keep a safe distance from the vehicle in front. The driver selected a target speed that was maintained if there were no slower leading vehicles. Selected speed was indicated by light emitting diodes (LEDs) around the speedometer. When a lead vehicle was detected by the ACC, an amber car symbol would illuminate on the dashboard. The ACC control switches were placed on the direction indicator stalk on the left side of the steering wheel. All 20 participants drove both with and without ACC.

The driving task, which included both free-flow driving and car-following, was performed on a 2-lane road, along a 100 km test route with random oncoming traffic. Speed, lateral position, and time headway were recorded and analyzed for all test rides. Subjective workload was assessed with the NASA-RTLX rating scale (Byers, Bittner, & Hill, 1989). Finally, questionnaires were used to collect the participants’ opinion concerning speed and distance control, and ACC usability.

Key results. A number of interesting results were found from this simulator test:

- ACC reduced workload and decreased physical discomfort
- ACC improved speed and distance control as experienced by the drivers
- ACC speed feedback was considered to be well designed
- ACC control switches were not optimal with respect to the use of hand controls
- ACC driving produced a shorter mean time headway compared to manual driving

In this article we describe and discuss the time headway, feedback and control findings that were used in the development of specific TELSCAN design guidelines for the design of ACC to support elderly and disabled drivers.

Mean time headways. The car-following situations were analyzed with respect to mean headway, variation in headway and shortest headway. Headway was calculated as the time it would take to drive the current distance to a leading vehicle with the current speed. Fourteen car-following situations were included in the analysis.

The mean time headway was longer for the unsupported condition -- driving without ACC -- compared to driving with ACC (Table 1). The longest mean headway was found when the dual lever users drove without ACC. A two-way ANOVA revealed a main effect of ACC F(1,36) = 8.82, p = .0053, but no effect of type of hand controls, and there were no significant interactions.

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<th>Single Lever System</th>
<th>Dual Lever System</th>
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<tr>
<td>With ACC</td>
<td>2.56</td>
<td>2.61</td>
<td>2.59</td>
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<tr>
<td>Without ACC</td>
<td>3.19</td>
<td>3.42</td>
<td>3.31</td>
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<td>Both</td>
<td>3.02</td>
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The ACC system tested was using a shorter mean time headway than preferred by people with lower limb disabilities. This was a first step towards a more specific guideline for ACC systems that are designed for all.

DESIGN GUIDELINES FOR ACC SYSTEMS

As ACC systems are not yet available on the market and only limited testing has been performed so far, there has been little guidance on how the ACC should be designed (e.g., International Standards Organization Technical Committee 204 Transport Information and Control Systems, Working Group 14 Vehicle/Roadway Warning and Control; Ross et al., 1996) and virtually nothing with respect to drivers with disabilities. The TELSCAN project took the results on time headway from the simulator test as input to the development of guidelines for ACC systems that would better include the needs of elderly and disabled people. It is recommended, however, that the guidelines proposed here be further tested in real traffic and during long-term usage. These guidelines are considered just a beginning in the difficult search for guidelines specific enough, but not too prescriptive to restrict innovative design.

As a result of the study of users’ requirements and the simulator testing, the following guidelines for ACC form part of the TELSCAN Handbook of Design Guidelines for Usability of Systems by Elderly and Disabled Travellers (Nicolle & Burnett, 1999).

**ACC Guideline: Adjustable Headway**

It is important that headway is individually adjustable, by a qualified specialist, according to the driver’s characteristics and preferences. People with different types of impairments should be included when the adjustable range of the headway is determined. This need for adjustable headway becomes even more pronounced in poor weather conditions, or nighttime driving, or when the severity of a driver’s impairment increases. Headway should not be altered by the driver, especially not while driving. As a starting point it is recommended that the ACC system uses a headway which is 0.7 seconds longer compared to that used for able-bodied drivers.

**Example.** An often-used headway value is 1.4 seconds in ACC systems. This value should be prolonged to 2.1 seconds (Peters, 1996). It is recommended, however, that testing in real traffic is undertaken to validate this guideline.

**Rationale.** An evaluation of one ACC system with drivers with lower limb impairments (Peters, 1996) revealed that this group of drivers prefer a longer average headway, or distance to a leading vehicle, than that which the system used. The study found that mean headway was approximately 0.7 seconds shorter for the ACC condition. This means that on average the participants were driving 17 m closer at a speed of 90 km/h to the leading vehicles. This shorter distance was accepted but it does not conform to the distances found under the unsupported condition. Some participants explicitly stated that the ACC used headway that was too short.

**ACC Guideline: Relevant Feedback**
The input and output of the ACC should be designed with respect to the function provided as viewed by the driver. Do not allow the driver to believe that it is a Collision Avoidance System (CAS) instead of an ACC by displaying irrelevant information (Peters, 1996).

**Example.** Explicitly displaying that a vehicle is in front might make the driver think the system has the functionality of a Collision Avoidance System, even if this is not the case.

**Rationale.** The purpose of an ACC system is to assist the driver in controlling the speed of the vehicle. But the extended functionality of ACCs, compared to conventional cruise controls, might confuse the driver, who might expect to be able to use it as a Collision Avoidance System. It is very important, therefore, to make this distinction clear to all drivers, especially when the feedback or information presentation subsystem of the ACC is designed (Ross et al., 1996; Peters, 1996). With respect to the ACC system tested (Peters, 1996), information about detection of the lead vehicle could be confusing to the driver.

**ACC Guideline: Adaptable Controls**

It should be possible to adapt the ACC controls easily so that they can be operated simultaneously with the primary driving task, but without interfering with it.

**Example.** If the ACC controls are placed on an acceleration lever for drivers requiring hand controls, then the driver could activate the ACC at the same time as controlling the speed (Peters, 1996).

**Rationale.** In the evaluation of an ACC system with drivers with lower limb impairments, the controls were placed on the direction indicator stalk at the left hand side. However, one switch had three different effects depending on the status of the ACC. The switches were obscured by the steering wheel which made it difficult visually to identify the controls. In order to operate the switches, it was necessary for the driver to release his/her hand from the steering wheel. The study found that it is important that the ACC controls are adaptable to cater for such requirements, regardless of the type of hand controls used for accelerator and brakes.

**ACC Guideline: Integrated Feedback**

The ACC feedback to the driver should be integrated into existing instruments as far as possible, as long as relevant information can be accurately and quickly deduced (Peters, 1996). Feedback from the ACC should also be adaptable so that the needs of individual drivers with disabilities can be considered.

**Example.** In the tested ACC system, feedback was considered well designed and integrated into existing instruments, using the original speedometer to display selected speed. When the ACC was switched on, the word CRUISE would appear in amber at the lower right on the dashboard. The speedometer had a circle of amber LEDs that were lit to display the currently selected speed, as long as the driver did not brake or turn the ACC off. From this testing, however, it is not possible to provide a specific guideline on appropriate feedback for an ACC system. In order to do this, it would be necessary to compare one system with another, and this needs testing in the future.

**Rationale.** Integrating the ACC feedback into existing instruments will enable parallel processing by the driver, meaning that the driver will more easily be able to process two pieces of information simultaneously (Stokes, Wickens, and Kite, 1990). Thus, the time and
effort required to obtain information from multiple sources should be reduced, leading to reduced workload and higher efficiency. This is important for all drivers, but especially for people who are experiencing higher workload due to their disability.

CONCLUSIONS

The TELSCAN Handbook of Design Guidelines for Usability of Systems by Elderly and Disabled Travelers (Nicolle & Burnett, 1999) is beginning to fill some of the gaps present in current guidelines. The Handbook will be further developed through TELSCAN’s continued surveys and empirical evaluation of other guidelines and system prototypes. It forms an important part of TELSCAN’s database on the World Wide Web and can be downloaded from the following WWW address: http://hermes.civil.auth.gr/telscan/telsc.html.

Many of these guidelines are still too general and more specificity would better assist the designer to include the needs of people who are older or disabled. Although general guidelines are necessary, the most specific and useful guidelines emerge only when carefully chosen research questions -- such as those posed during the simulator testing described in this article -- can be investigated.

However, even when designers have guidelines in an accessible format, there is still much work to be done. Further increased awareness is needed so that designers know not only which guidelines are available but also when to use them. To facilitate this process, developers of guidelines for ITS should work together in coordinating their efforts and integrating their guidelines, thus providing a ‘one-stop shop’ for designers wherever possible.

Always including people with physical, perceptual and cognitive impairments in the design, development and evaluation of ITS will make such systems more usable and safer for everyone. Indeed, the ‘temporarily able-bodied’ traveller may also benefit from such research in the 3rd millennium.

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REFERENCES


Paper IV

Human Factors Aspects on Joystick Control of Adapted Cars

Human factors aspects on joystick control of adapted vehicles

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Abstract

An experiment was set-up to investigate different joystick designs based on steer-by-wire technology. The experiment was carried out in a driving simulator. Both driving behaviour and perceived control of the car was registered and analysed. All participants had a SCI (Spinal Cord Injury) at cervical level, i.e. drivers with tetraplegia. Two types of joysticks were tested, one conventional (similar to what is used with computer games) and one modified with which the driver could control speed and steering independently. Both joysticks were tested with and without active feedback. The driving task consisted of rural road driving and a manoeuvre test with a double lane-change.

The results presented here should be considered as preliminary and the study as a pilot study, which will be completed with a larger set of participants. So far 8 subjects have completed the experiment. The preliminary results cannot be used to draw any definite conclusion on which system design should be preferred. There was some evidence that active feedback provided a better lateral control and the drivers drove with larger safety margins with the modified joystick. However, the drivers' opinion seemed to be more in favour of the conventional passive joystick.

Introduction and background

The ordinary primary driving controls in a standard production car, i.e. steering wheel, accelerator and brake pedals, provide feedback to the driver and utilise a rational control distribution on the driver's hands and feet. However, drivers with so severe disabilities that they cannot drive a conventional car could benefit from an alternative design of the primary controls. The emerging steer-by-wire technology will enhance the freedom to design a more accessible environment for drivers with disabilities. However, the replacement of conventional controls with steer-by-wire controls should be made in a way that the driver has equal or better control of the car compared with drivers of conventional cars.
In Sweden there are today a small number of drivers with severe disabilities that drive their cars with a four-way joystick (Östlund, 1999). The drivers control the car with one single lever, lateral motions to control steering and longitudinal motions to control speed (accelerator and brake). The most frequent longitudinal control is to pull backwards for accelerating and to push forward to brake. Results from a manoeuvre test on a closed track revealed that these drivers had some difficulties controlling the car, which was interpreted as a result of inference between lateral and longitudinal control and lack of control feedback (Östlund & Peters, 1999). For instance the divers had difficulties controlling the brake function to make a smooth stopping manoeuvre. This problem could be due to lack of feedback in the control, as the joysticks used did not provide any feedback. Braking in a curve was a manoeuvre, in which problems of control interference revealed themselves. As the driver started to brake steering was also effected. It was difficult for the driver to know how to move the lever in order to brake without influencing the steering. This problem was attributed to the fact that the joystick functions as a coupled system. Ideal would be that the drives could control steering and accelerating/braking independently. This could be achieved with an uncoupled system. An additional problem observed was time lags in the steering function. The current experiment was set-up in order to study a joystick design that might solve these problems.

An additional objective was to contribute to the development of an evaluation method for adapted cars. Current driving license legislation prescribes that drivers with physical disabilities are only allowed to drive if the vehicle is adapted in a way that the disabilities are full compensated. However, the directives do not describe how to determine whether the compensatory goals have been achieved (Peters, 2001). Standardised methods to evaluate adaptations with respect to driver’s disabilities should be developed and tested (Peters, Fulland, Falkmer, & Nielsen, 2000). A critical aspect in such an evaluation is to determine if the driver can drive with sufficient safety margins. The current experiment aimed at contributing to the development of such a method.

Three hypothesis were formulated on the basis of the problems described above:

1. Active feedback (i.e. providing the driver with feedback forces normally felt in pedals and steering wheel) will improve the driver’s control of the vehicle and thus improve driving performance. Both physical and mental workload will be lower with active compared to passive feedback (i.e. only centring spring forces).
2. The uncoupled control design will improve the driver’s control of the vehicle compared to the coupled control. Both physical and mental workload will be lower with the uncoupled control.
3. Best performance, lowest workload, and best opinion will be observed for the condition with both active feedback and uncoupled control.

A within subject design was applied and two factors were manipulated: feedback (active, passive) and the design of lateral and longitudinal control function (coupled and uncoupled). The two physical joystick designs are identified as conventional and
modified in the following. All subjects drove under all four conditions. The order of conditions was counterbalanced.

**Method**

The experiment was carried out in a driving simulator in order to have better control of vehicle parameters and driving conditions. This also simplified the installation of the joystick systems that were tested.

**Subjects**

The drivers who use joystick-controlled car today are severely disabled and move around sitting in their electric wheelchairs. It was not possible for these drivers to enter and drive in the moving-base simulator that was used in this experiment. Thus, it was needed to find another suitable and relevant group of drivers. Drivers with Spinal Cord Injuries (SCI) constitute the largest group of drivers of adapted cars (Peters, 1998; Henriksson, 2001). The selection of participants was preceded by discussions with both medical and paramedical specialists at a rehabilitation clinic and an experienced vehicle adaptation company. It was decided that a relevant group of drivers would be driver with high level SCI, i.e. drivers with tetraplegia. These drivers are paralysed from the level of their nipples down to their toes due to a lesion in the cervical region of the spine. Their arm and hand functions are also impaired but only those with sufficient arm and hand function were selected. The recruiting of participants was made with the help of the rehabilitation clinic and a SCI interest group.

Eight subjects, seven males and one female, participated in this pilot study. The average age for the participants was 39 years (std = 8 years), their SCI level varied from 4th to 7th cervical vertebrae. They drove on average 26,250 km (std = 9,900 km) annually and had on average held a driving licence for an adapted vehicle for 16 years (std = 8 years). The total driving experience was somewhat higher as some subjects already possessed a driving licence at the time of injury. The person with the least experience as driver of adapted cars had 15 years of experience as a driver of standard cars. Two were sitting in their electric wheelchairs while driving their own cars. Two used a sliding board to transfer from their wheelchair to the driver’s seat. All subjects were unfamiliar with joystick driving.

**Driving simulator**

A dynamic, high fidelity, moving base driving simulator was used in this study (Nilsson, 1989; Nordmark, 1990). The simulator consisted of six subsystems. The vehicle was modelled in the computer system and the moving base system simulated accelerations in three directions through roll, pitch and linear lateral motions. The visual system presented the external scenario in the form of computer-generated graphics on a 120° wide screen, 2.5 meters in front of the driver. The sound system generated noise and infrasounds that resembles the internal auditory environment in a modern passenger car. The vibration system simulated the sensations the driver experience from the contact between the road and the vehicle. A temperature system
controlled the air temperature in the driver's cab. A number of validation studies have successfully been performed in this simulator (Törnros, Harms, & Alm, 1997). These studies showed that the moving base system was important for the experienced reality and external validity. The car body consisted of Volvo 850. The simulator was accessed by a wheelchair lift and the subjects were assisted, if needed, when transferring from their wheelchair to the drivers seat. The standard steering wheel was removed in order to facilitate ingress and egress. The drivers were sitting in the original driving seat and used the standard safety belt. An extra postural support belt was available if needed.

**Adaptation**

On the basis of the results from the earlier manoeuvre test (Östlund & Peters, 1999; Östlund, 1999), the following were developed:

1. Algorithms that controlled how steering, accelerator and brake reacted to joystick movements.
2. An alternative joystick design, which would allow independent lateral and longitudinal control (uncoupled system).
3. Feedback algorithms.

Steering commands were speed dependently downscaled to maintain accurate steering control at all speeds. A constant lateral joystick angle was translated to a constant lateral acceleration at all speeds above 40 km/h, which resulted in a maximal lateral acceleration of 0.6g at all speeds above 40 km/h. The algorithms were developed to consider vehicle dynamics. Steering commands were filtered (4 Hz lowpass) to simulate the effect of a steering servo. Accelerator and brake were controlled with a force which deflected the joystick; forward to brake and backward to accelerate. There was a linear relation between forces on the joystick and accelerating-/braking effect.

For the active feedback condition, normal steering wheel momentum and the effects of damping were fed back as lateral forces in the joystick. Also a spring force was generated in the joystick in order to centralise the lever into neutral position. For the passive feedback condition, only spring forces were used.

Two physical joystick designs were used in the experiment. Both were based on a commercial system made by Immersion Corporation. The first one, called conventional, looked like an ordinary joystick for computer games but the lever was replaced with a grip developed for drivers with tetraplegia. With this system was the lateral and longitudinal control function coupled. In the second system, called modified, were the lateral and longitudinal control functions uncoupled. The uncoupling of steering and speed control was implemented by modifying the joystick so that speed was controlled with linear back/forth arm motions, and steering was controlled with rotational motions around an axis through the arm (See figure 1).

The joystick was controlled by a separate PC, which communicated with the simulator’s computer via a CAN bus connection.
Figure 1. Modified (left) and conventional (right) joystick. The top pictures show how the two joysticks were held by the drivers. Max. feedback forces were 1.2 Nm for all angular motions and 37 N for the linear brake/accelerate motion for the modified joystick.

Driving task

The primary objective with the experiment was to find out which of the four joystick designs was best with respect to performance (safety marginal), workload, and driver opinion. Driving was limited to vehicle control and to a limited extent interaction with other road users. The driving task included both ordinary driving on a rural road and a set of double lane-change manoeuvres. All subjects drove in each of the four conditions:

- 20 km rural road driving training
- 3 double lane-changes training
- 20 km rural road driving
- 3 double lane-changes
- 20 km rural road driving
- 3 double lane-changes

All drivers drove a training session of 20 km rural road driving and a set of lane-change manoeuvres before the actual driving test for all four conditions. The drivers were encouraged to try out how the joystick worked during the training sessions.

Rural road driving

The participants were instructed to drive as they normally do when driving on a rural road for the actual test conditions. While driving on the road the participants caught up with lead vehicles twice. The instruction was to follow the cars, as they would normally do and eventually overtake the car when it turned on the right direction indicator. The lead vehicles’ speed varied during the following situation. The driving
conditions were daylight, full friction, summer, varying curvature (lateral and horizontal), and random oncoming traffic.

Double lane-change
The instructions to the participants were to drive between the cones and make a double lane-change at 50 km/h without hitting any cones. The physical dimensions of the lane-change manoeuvre track are shown in figure 2. The lane-change was designed according to ISO 3888-1 (ISO, 1999) but the speed recommended in the standard is higher (80 km/h). The lane width was calculated according to the standard with a vehicle width of 1.76 m.

![Figure 2. Double lane-change according to ISO 3888-1. Lane width in section A: 2.19 m, section B 2.36 m and in section C: 2.54 m.](image)

Procedure
The participants drove at two occasions. At each occasion they drove with either conventional or modified joystick with both passive and active feedback. The subjects were given a written description of the experiment before entering the simulator. A recording device, Vitaport 2, was used to collect physiological workload data. After the training session the car was stopped and the driver was asked if the driving position and postural support was sufficient and if anything else needed to be changed. After each of the four joystick conditions the drivers were asked a number of questions concerning their opinion about the joystick. In addition, they were asked about their opinion about the joystick design after each driving occasion and finally some additional questions when all four driving conditions were completed.

Measures
The simulator’s computer was used to collect driving performance data. The sampling rate was 50 Hz, and the storage rate was 20 Hz. Hence, measures based on time calculations had 1/50 (20 ms) accuracy. The following basic data were collected:

1. Driving performance measures:
   - (Longitudinal) Speed (m/s)
Joystick control of adapted vehicles

- Joystick lateral position, and corresponding steering wheel position. These are not the same since joystick steering commands were scaled and filtered before transmitted to the simulator as a steering wheel angle.
- Joystick longitudinal position (gas/brake commands).
- Lateral position (metres). Lateral position was defined as the distance between the centre of the car to left lane marking. The accuracy was 0.01 m.
- Standard deviation of lateral position (SDLP) (m).
- Time To Lane Crossing (TLC) (s). TLC was calculated in real time with 20 ms accuracy.
- Time to collision (TTC) and time headway to lead vehicles (seconds).

2. Questionnaires

- Background data (age, gender, driving experience etc.)
- Subjective performance and workload
- Subjective evaluation of adaptation

The following physiological data were captured: Electrocardiogram, which was used to calculate e.g. Heart Rate Variability, and Electromyogram on the Right Deltoid Anterior and the Right Arm’s Trapezius (muscles that were used to control the joystick). The results of these measures are not included in this report.

*Safety margins for driving on rural road*

Appropriate and relevant safety margin measures are needed for a reliable adaptation evaluation. TLC is a good cue to determine a driver’s lateral position control and thus the lateral safety marginal. TLC is a measure of how well the driver is following the road geometry. TLC is measured as the distance to line crossing along the vehicles path divided by the speed of the vehicle. TLC is quite easy to calculate in a driving simulator where everything is known about the vehicle and the environment. However, two major problems with TLC are the complexity of its computation in real time, and that it is computed differently on straight road segments compared to curved segments (van Winsum, Brookhuis, & de Waard, 1998). Therefore it has been suggested to use an approximation of the real TLC measure. Van Winsum, Brookhuis and de Waard (1998) found that simply using only lateral position and lateral velocity is not sufficient calculate TLC accurately but if the change in lateral velocity is included in the approximation the result corresponds well to the real TLC especially with respect to minimum (min) TLC. The TLC approximation was used in this experiment.

Time To Collision (TTC) and Time Headway can be used to determine the longitudinal safety marginal. Time Headway is calculated as the headway distance to a lead vehicle divided by the speed of the lag car. TTC is computed as the headway distance divided by the speed difference between the vehicles or the approaching speed. Headway distance is defined as the distance from the lead car’s back to following car’s front.
Performance of lane-change manoeuvres
A number of derived measures were defined in order to evaluate the lane-change manoeuvres. The task was to maintain constant speed while making a lane-change without hitting any cones. The number of cones hit was taken as a critical measure. Variation in speed for the total manoeuvre and for the two critical steering manoeuvres when moving from right to left and then back to right again was considered critical for manoeuvre control. An ideal manoeuvre was calculated and the deviation from this was also used as a measure of lane-change control.

Results
Both free driving and lane-change manoeuvres were repeated for the different conditions. Averages, standard deviations (as a measure of variation) were calculated for most measures and the number of data entries included in the calculations will be specified in the following. Two-way ANOVAs were used to evaluate the results and the significance level was set to $p < .05$.

Driving performance
Free driving on rural road
Free driving was defined as the total driving distance when the driver was not in a car-following situation. The results from free driving are shown in table 1. The average speed for all of the four conditions was close to 90 km/h. The speed was slightly lower for the modified joystick condition and least for passive modified joystick. The differences were, however, non-significant. The variation in speed (standard deviation) followed the same pattern but also these differences were non-significant. Several measures were used to investigate the steering control. The drivers’ ability to use the joystick to steer the car was measured with the variation in lateral joystick motion, while the road geometry was compensated for. It was found that the active condition for both conventional and modified joystick resulted in significantly less lateral motion.

The analysis of average lateral position revealed a significant interaction effect. The drivers drove closer to the right lane border with the passive conventional joystick compared to the active while for the modified joystick the effect was reversed. Standard deviation of lateral position, min (of min TLC) i.e. the smallest positive TLC recorded did not differ significantly for the four conditions. The very low values of the TLC right shows that the drivers preferred to drive very close to the right hand side of the road. They even crossed the lane marker several time as indicated by the measure “No of crossings right”. It should be noted that there was a hard shoulder of 1 m to right hand. When looking at the mean (of min) TLC right measure it was found that there was an effect of joystick design, i.e. they drove with a significantly greater safety margin to right with the modified joystick. Also the number of lane border crossings to right was lower for the modified joystick compared to the conventional. All lateral control measures indicated that the drivers tended to keep to the right.
Table 1. Result of the analysis of free driving on rural road (2 x 20 km for each condition and subject). The $F$ [$F(1,7)$]-value and level of significance together with observed power are shown where relevant. Non-significant differences are indicated by Ns in the table. C = conventional, M = modified, P = passive, A = active

<table>
<thead>
<tr>
<th>Parameter</th>
<th>CA</th>
<th>CP</th>
<th>MA</th>
<th>MP</th>
<th>CM</th>
<th>AP</th>
<th>CM x AP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean speed (km/h)</td>
<td>91.0</td>
<td>93.9</td>
<td>90.2</td>
<td>89.8</td>
<td>Ns</td>
<td>Ns</td>
<td>Ns</td>
</tr>
<tr>
<td>Std speed (km/h)</td>
<td>4.76</td>
<td>4.61</td>
<td>4.49</td>
<td>4.46</td>
<td>Ns</td>
<td>Ns</td>
<td>Ns</td>
</tr>
<tr>
<td>Std lateral joystick motion (degrees)</td>
<td>0.96</td>
<td>1.11</td>
<td>0.97</td>
<td>1.10</td>
<td>Ns</td>
<td>Ns</td>
<td>Ns</td>
</tr>
<tr>
<td>Mean lateral position (m)</td>
<td>2.15</td>
<td>2.21</td>
<td>2.09</td>
<td>2.07</td>
<td>Ns</td>
<td>Ns</td>
<td>F=5.9, p=.046 (0.6)</td>
</tr>
<tr>
<td>Std lateral position SDLP (m)</td>
<td>0.21</td>
<td>0.21</td>
<td>0.21</td>
<td>0.23</td>
<td>Ns</td>
<td>Ns</td>
<td>Ns</td>
</tr>
<tr>
<td>Min TLC Right (s)</td>
<td>0.01</td>
<td>0.06</td>
<td>0.05</td>
<td>0.01</td>
<td>Ns</td>
<td>Ns</td>
<td>Ns</td>
</tr>
<tr>
<td>Min TLC Left (s)</td>
<td>1.34</td>
<td>1.44</td>
<td>1.60</td>
<td>1.25</td>
<td>Ns</td>
<td>Ns</td>
<td>Ns</td>
</tr>
<tr>
<td>Mean (min) TLC R (s)</td>
<td>2.18</td>
<td>1.90</td>
<td>2.38</td>
<td>2.18</td>
<td>F=8.9, p=.021 (0.7)</td>
<td>Ns</td>
<td>Ns</td>
</tr>
<tr>
<td>Mean (min) TLC L (s)</td>
<td>5.99</td>
<td>5.83</td>
<td>5.80</td>
<td>5.35</td>
<td>Ns</td>
<td>Ns</td>
<td>Ns</td>
</tr>
<tr>
<td>No of crossing R</td>
<td>15.4</td>
<td>19.1</td>
<td>13.6</td>
<td>14.2</td>
<td>Ns</td>
<td>Ns</td>
<td>Ns</td>
</tr>
<tr>
<td>No of crossing L</td>
<td>0.31</td>
<td>0.13</td>
<td>0.19</td>
<td>0.31</td>
<td>Ns</td>
<td>Ns</td>
<td>Ns</td>
</tr>
</tbody>
</table>

Car following situations
In all there were 16 car following situations per subject that were included in the evaluation, 4 per condition for all subjects. When the driver was 100 metres behind the lead vehicle, its speed started varying according to sinus function between 65 and 75 (km/h) for 40 seconds. The subjects were instructed to follow the car as they would do in a real situation and to overtake as the lead vehicle’s right direction indicator started to flash. Distance, TTC and time headway data were used to analyse the car following situations. Table 2 shows the group averages results for three safety critical measures, min. distance, min. time headway, and min. TTC. It can be seen that the drivers on average kept a rather large distance in metres and time to the vehicle in front. It also turned out the individual differences were considerable for all three measures. The standard deviation varied between 4.7 and 8.3 across all three parameters. Thus, it seems like the car-following situation was not experienced as safety critical.
Table 2 Results of analysis group averages of parameters used to evaluate car following situations (average over 4 situations per condition and subject). Ns = Non-significant. C = conventional, M = modified, P = passive, A = active

<table>
<thead>
<tr>
<th>Parameter</th>
<th>CA</th>
<th>CP</th>
<th>MA</th>
<th>MP</th>
<th>CM</th>
<th>AP</th>
<th>CM x AP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min distance (m)</td>
<td>15.5</td>
<td>15.5</td>
<td>15.9</td>
<td>15.6</td>
<td>Ns</td>
<td>Ns</td>
<td>Ns</td>
</tr>
<tr>
<td>Min. Time (s)</td>
<td>12.9</td>
<td>13.0</td>
<td>13.4</td>
<td>13.4</td>
<td>Ns</td>
<td>Ns</td>
<td>Ns</td>
</tr>
<tr>
<td>Headway (s)</td>
<td>14.2</td>
<td>14.1</td>
<td>15.0</td>
<td>15.0</td>
<td>Ns</td>
<td>Ns</td>
<td>Ns</td>
</tr>
</tbody>
</table>

Double lane-change manoeuvre
All rural road driving was followed by three lane-change manoeuvres. This means that all drivers for each of the four joystick conditions made 6 lane-change manoeuvres that were included in the analysis. One subject did not perform the lane-change manoeuvres due to motion sickness. Both steering and speed control were analysed. The results are shown in Table 3. The drivers were instructed to make the lane-change at a constant speed 50 km/h. The results show that the group means were approximately the same for all four conditions. Also speed variations were similar with a slightly lower value for the conventional passive joystick.

Table 3 Result of analysis of lane-change manoeuvre (average over 2 x 3 trials per condition and subject). The F [F(1,6)]-value and level of significance together with observed power are shown where relevant. Non-significant differences are indicated by Ns in the table. C = conventional, M = modified, P = passive, A = active, \(^1\) = km/h, \(^2\) = degrees

<table>
<thead>
<tr>
<th>Parameter</th>
<th>CA</th>
<th>CP</th>
<th>MA</th>
<th>MP</th>
<th>CM</th>
<th>AP</th>
<th>CM x AP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean speed (^1)</td>
<td>50.2</td>
<td>51.0</td>
<td>51.5</td>
<td>50.9</td>
<td>Ns</td>
<td>Ns</td>
<td>Ns</td>
</tr>
<tr>
<td>Std speed (^1)</td>
<td>2.19</td>
<td>2.48</td>
<td>2.49</td>
<td>2.48</td>
<td>Ns</td>
<td>Ns</td>
<td>Ns</td>
</tr>
<tr>
<td>Std speed (1(^{st}) lane-change)(^1)</td>
<td>0.63</td>
<td>0.64</td>
<td>0.52</td>
<td>0.54</td>
<td>Ns</td>
<td>Ns</td>
<td>Ns</td>
</tr>
<tr>
<td>Std speed (2(^{nd}) lane-change)(^1)</td>
<td>0.68</td>
<td>0.71</td>
<td>0.65</td>
<td>0.74</td>
<td>Ns</td>
<td>Ns</td>
<td>Ns</td>
</tr>
<tr>
<td>Std longitudinal joystick motion(^2)</td>
<td>1.59</td>
<td>1.64</td>
<td>1.56</td>
<td>1.69</td>
<td>Ns</td>
<td>Ns</td>
<td>Ns</td>
</tr>
<tr>
<td>Std lateral joystick motion(^2)</td>
<td>9.66</td>
<td>9.73</td>
<td>10.31</td>
<td>10.37</td>
<td>Ns</td>
<td>Ns</td>
<td>Ns</td>
</tr>
<tr>
<td>Deviation from “ideal” lane-change (m)</td>
<td>0.19</td>
<td>0.17</td>
<td>0.19</td>
<td>0.21</td>
<td>Ns</td>
<td>Ns</td>
<td>F=7.30, p=.036 (0.6)</td>
</tr>
<tr>
<td>No. of cones hit</td>
<td>0.17</td>
<td>0.24</td>
<td>0.40</td>
<td>0.33</td>
<td>Ns</td>
<td>Ns</td>
<td>F=7.50, p=.034 (0.6)</td>
</tr>
<tr>
<td>No. of joystick turns</td>
<td>17.8</td>
<td>20.3</td>
<td>17.0</td>
<td>19.5</td>
<td>Ns</td>
<td>Ns</td>
<td>Ns</td>
</tr>
</tbody>
</table>

It was expected that speed keeping during the actual lane-change would be difficult and critical. Therefore, standard deviation of speed was analysed for the two turns. The variation in speed for the first, right turn was lower for the modified joystick compared to the conventional. But the difference was non-significant. For the second
turn it seems to be more of a difference between active and passive conditions. The same types of differences were found when considering the actual longitudinal joystick motions. However, again none of the differences were significant.

The lateral control was analysed by first looking at how much the drivers moved the joystick laterally. It was found that the group means were greater for the modified version and slightly higher for the passive compared to the active. None of these differences were significant. The deviation from an ideal lane-change was used to evaluate the quality of the lane-change manoeuvre. The ideal lane-change was defined as follows. First, the route for constant lateral speed lane-changes was calculated. To make the route continuous and conform to lateral manoeuvres with real cars, the route was low pass filtered. The cut off frequency was set at 3.5 Hz, which approximately corresponds to cut off frequency of steering systems of modern car (Zomotor, 1987). The analysis revealed a significant interaction effect. The deviation increased for the passive condition when using the conventional joystick while it decreased for the modified joystick. Yet, another way to analyse the lateral control was done when looking at how many times the drivers changed lateral motion of the joystick from right to left and vice versa. It was found that the driver made on average more turns with the passive joysticks compared to the active. This difference was also significant. Finally, the number of cones hit was used as an indicator of well the manoeuvre was performed. The lowest value was found for the conventional joystick with active feedback and the highest for the modified with active feedback. However, the differences were non-significant.

Initially there was an additional manoeuvre test included in the experiment, braking in a curve. This type of manoeuvre proved to be critical in the previous experiment on a closed track (Östlund & Peters, 1999). However, it turned out that these manoeuvres caused sever feeling of sickness in the simulator for some participants. It was assumed that the driving simulator’s motion system was not able to sufficiently well reproduce the very complex forces acting on the driver in a real situation. It was decided to abandon this manoeuvre in this experiment.

Drivers’ opinion

The drivers were asked about their opinion about the joystick system they had been driving with directly after each of the four driving conditions. The questionnaire consisted of 15 questions and was divided into two sections: the first one contained questions relating to driving on the rural road and the second consisted of questions concerning the lane-change manoeuvres. The results are shown in Table 4. A seven point scale was used to indicate the respondents reply. The first question was how well the driver thought he/she had performed. The following three questions were questions concerning experienced workload. The final three concerned with driving on the road addressed how easy or difficult the driver thought it was to control the car, i.e. steering, accelerating, and braking. The same types of questions were asked in the second part of the questionnaire for the lane-change manoeuvres. A question concerning braking was taken away as the brake in a curve manoeuvre was excluded.
The result show that the participants thought that in general they performed less good in the lane-change manoeuvres, spent more effort and thought they had less good control compared to driving on the road. The conventional joystick with passive feedback seemed to be preferred over the others in most of the cases according to the drivers’ opinion. An analysis of variance showed that most of the differences shown in Table 4 were non-significant (see Table 5).

Table 4 Results (group mean values) of answers to questions concerning the drivers’ opinion about the four different joystick designs. The best score for each question is indicated by italic print in the table. The last row summarises the number of best scores per condition. C = conventional, M = modified, P = passive, A = active

<table>
<thead>
<tr>
<th>Question</th>
<th>CA</th>
<th>CP</th>
<th>MA</th>
<th>MP</th>
<th>Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>On the road (N = 8)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. How well did you perform?</td>
<td>5.38</td>
<td>5.50</td>
<td>5.13</td>
<td>5.00</td>
<td>1 = very bad</td>
</tr>
<tr>
<td>2. How much effort (mentally and physically) did you spend?</td>
<td>3.00</td>
<td>2.00</td>
<td>3.25</td>
<td>3.25</td>
<td>7 = very much</td>
</tr>
<tr>
<td>3. Mental effort?</td>
<td>3.75</td>
<td>3.38</td>
<td>3.50</td>
<td>3.38</td>
<td>7 = very much</td>
</tr>
<tr>
<td>4. Physical effort?</td>
<td>2.13</td>
<td>1.75</td>
<td>2.00</td>
<td>1.75</td>
<td>7 = very much</td>
</tr>
<tr>
<td>5. Steering control?</td>
<td>3.00</td>
<td>2.38</td>
<td>3.25</td>
<td>3.88</td>
<td>7 = very difficult</td>
</tr>
<tr>
<td>6. Accelerator control?</td>
<td>2.50</td>
<td>2.00</td>
<td>3.00</td>
<td>3.38</td>
<td>7 = very difficult</td>
</tr>
<tr>
<td>7. Brake control?</td>
<td>3.38</td>
<td>2.63</td>
<td>3.63</td>
<td>3.00</td>
<td>7 = very difficult</td>
</tr>
<tr>
<td>8. Simultaneous steering, acceleration, braking control?</td>
<td>3.00</td>
<td>2.63</td>
<td>3.63</td>
<td>3.38</td>
<td>7 = very difficult</td>
</tr>
<tr>
<td>Manoeuvres (N = 7)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9. How well did you perform?</td>
<td>4.86</td>
<td>4.57</td>
<td>4.43</td>
<td>4.57</td>
<td>1 = very bad</td>
</tr>
<tr>
<td>10. How much effort (mentally and physically) did you spend?</td>
<td>3.00</td>
<td>2.86</td>
<td>3.00</td>
<td>3.57</td>
<td>7 = very much</td>
</tr>
<tr>
<td>11. Mental effort?</td>
<td>3.57</td>
<td>3.29</td>
<td>3.14</td>
<td>3.29</td>
<td>7 = very much</td>
</tr>
<tr>
<td>12. Physical effort?</td>
<td>2.14</td>
<td>2.14</td>
<td>2.14</td>
<td>2.57</td>
<td>7 = very much</td>
</tr>
<tr>
<td>13. Steering control?</td>
<td>2.57</td>
<td>3.43</td>
<td>3.29</td>
<td>3.50</td>
<td>7 = very difficult</td>
</tr>
<tr>
<td>14. Accelerator control?</td>
<td>3.29</td>
<td>3.71</td>
<td>4.43</td>
<td>3.83</td>
<td>7 = very difficult</td>
</tr>
<tr>
<td>16. Simultaneous steering, acceleration, braking control?</td>
<td>4.00</td>
<td>4.20</td>
<td>4.00</td>
<td>3.83</td>
<td>7 = very difficult</td>
</tr>
<tr>
<td># Scored best</td>
<td>4</td>
<td>10</td>
<td>2</td>
<td>3</td>
<td></td>
</tr>
</tbody>
</table>

Only two significant differences were found. Brake control was experienced as easier for the passive condition while steering control during the manoeuvres was easier with the active feedback.

Effects of learning

In order to minimise the influence of learning the order of conditions were counterbalanced. In addition, all four driving conditions were preceded by a training session. Thus, it was interesting to know if learning affected the results. Figure 3 and
show some examples of how steering control performance for both driving on the road and lane-change manoeuvres evolved over time.

Table 5. Result of two-way ANOVA tests on the result of questions to the drivers. Level of significance was set to 5%. CM = Conventional/Modified, AP = Active/Passive, Ns = Non-significant.

<table>
<thead>
<tr>
<th>Question</th>
<th>CM</th>
<th>AP</th>
<th>CM * AP</th>
</tr>
</thead>
<tbody>
<tr>
<td>On the road N=8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. How well did you perform?</td>
<td>Ns</td>
<td>Ns</td>
<td>Ns</td>
</tr>
<tr>
<td>2. How much effort (mentally and physically) did you spend?</td>
<td>Ns</td>
<td>Ns</td>
<td>Ns</td>
</tr>
<tr>
<td>3. Mental effort?</td>
<td>Ns</td>
<td>Ns</td>
<td>Ns</td>
</tr>
<tr>
<td>4. Physical effort?</td>
<td>Ns</td>
<td>Ns</td>
<td>Ns</td>
</tr>
<tr>
<td>5. Steering control?</td>
<td>Ns</td>
<td>Ns</td>
<td>Ns</td>
</tr>
<tr>
<td>6. Accelerator control?</td>
<td>Ns</td>
<td>Ns</td>
<td>Ns</td>
</tr>
<tr>
<td>7. Brake control?</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8. Simultaneous steering, acceleration, braking control?</td>
<td>Ns</td>
<td>Ns</td>
<td>Ns</td>
</tr>
</tbody>
</table>

Manoeuvres N=7(6)

| 9. How well did you perform?                                 |     |     |         |
| 10. How much effort (mentally and physically) did you spend? | Ns  | Ns  | Ns      |
| 11. Mental effort?                                           | Ns  | Ns  | Ns      |
| 12. Physical effort?                                         | Ns  | Ns  | Ns      |
| 13. Steering control?                                        | Ns  |     | Ns      |
| 14. Accelerator control?                                     | Ns  | Ns  | Ns      |
| 16. Simultaneous steering, acceleration, braking control?    | Ns  | Ns  | Ns      |

The training sessions were excluded. The diagrams do not reveal any obvious signs of continuous learning effects beyond the training. The free driving exercise was simple and drivers seemed to learn the lane-change manoeuvre rather fast.

Discussion

The results partly support the research hypotheses. However, it seems to be an open question which of the four joystick designs is superior. Looking at the results in general there is a contradiction between performance results and the drivers’ opinion. The driving performance results provide some support for the idea that active feedback is better than passive and that the modified joystick design was better than the conventional. However, the drivers’ opinion seems to be more in favour of the conventional joystick with passive feedback.
Figure 3. Evolution of steering control according to order of conditions in sequence

\[\text{Std Steering Angle (Joystick)}\]

Figure 4. Evolution of steering control according to order of conditions in sequence

Driving performance

Speed keeping on the rural road did not seem to be a problem. The variation in speed was lower for the modified joystick and this could be sign of better speed control even if the difference was not significant. The drivers’ choice of lateral position was interpreted as they felt more insecure with the conventional design and thus drove more to the right, away from the oncoming traffic. The variation in joystick motion beyond the actual steering commands needed to follow the road was significantly less for the active condition. This was interpreted as active feedback provided a better steering control. The min TLC R measure should be regarded with cautiousness as the drivers crossed the right border rather frequently. The min TLC
R data were calculated only for TLC > 0. The TLC mean value was, however, of more interest and the results showed that drivers drove with a greater safety margin with the modified joystick (significant) and best with the active feedback (non-significant). This was interpreted as a support for the assumption that the modified joystick with active feedback provided the driver with a better lateral control compared to the other conditions. The analysis of the car-following data did not provide any further useful information with respect to the hypotheses. The lane-change manoeuvres did however reveal some interesting differences. The speed variation was lowest for the conventional joystick with active feedback. However, the speed control during the two lane-changes tended to be better for the modified joystick with active feedback. However, none of these differences were significant. The analysis of steering control seems to indicate that active feedback can provide better steering control specifically for the modified joystick. It was also interesting to notice that the deviation from “ideal” lane change was close to the SDLP measure for free driving. This was taken as an indication that the definition of “ideal” was rather good. However, there is an obvious need to continue the investigation with more subjects. The safety margin measures used, e.g. TLC, deviation from “ideal” travel path seems to be relevant but needs to be further developed.

**Driver opinion**

The drivers’ own judgements about the tested joystick systems seems, at a glance, to be more clear cut compared to the driving performance results. The general opinion seems to be that the conventional joystick with passive feedback was superior with respect to performance, workload, and control when driving on the road. The differences were, however, non-significant. The only significant difference found for the rural road driving was that the passive condition was experienced as better for the braking control. However, it should be noted that the drivers did not specifically have to use the brake in this task. So the value of this finding can be disputed. The result of the lane-change questions were more scattered but the conventional joystick with active feedback seemed to be most preferred. The only significant difference was that active feedback seems to be experienced as providing better steering control. So even if there seems to be a general positive opinion in favour of the conventional joystick with passive feedback, no clear conclusions can be drawn. A possible reason why the drivers preferred the passive conventional joystick could be because it had a more familiar grip and that feedback increased system inertia and made it more loading/tiresome to use.

**Learning to use the joystick**

Practical experience with conventional joysticks has proved that it is difficult to drive with a joystick. The amount of time needed to learn to get control is far greater compared to the time needed to get acquainted with other adaptations. Drivers who use joystick systems have more severe impairments and this can of course influence the time needed to learn. It is interesting that all four tested joystick systems in this experiment seemed to be rather easy to learn how to use. After only 20 km driving and a set of lane change manoeuvres the drivers were able to drive at a speed of approx. 90 km/h. Driving in a simulator is different from real driving and the driving
task was relatively simple. However, the results are promising. All of the tested joysticks have practically no time lag, an important difference, which might explain why these were easier to use compared to current commercial systems. It is well-known that time lags in manual control systems are difficult for humans to handle (Wickens, 1992).

Conclusions

The current results will not allow any definite conclusions about which of the tested joystick designs is superior as the study was limited in nature. However, the following can be said:

- No definite answer on overall preferred type
- Further research needed, this was a pilot study
- Active feedback can improve control
- Uncoupled system can improve control
- Investigate users preferences further
- Absence of time lags can shorten learning time
- Other feedback and transfer functions should be tested

Acknowledgement

This experiment was carried out under a contract with Dr. J. Petzäll of the Swedish National Road Administration (SNRA). We like to thank the people at the Rehabilitation Clinic at the University Hospital of Linköping and Rekryteringsgruppen who helped us find participants for our experiment. We also like to thank all the participants who each spent six hours of driving in our simulator. Without them this would not have been possible. Finally, we like to thank Håkan Sehammar who programmed the simulator.

References


Paper V

Safety and Mobility for People with Disabilities Driving Adapted Cars

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Safety and Mobility for People with Disabilities Driving Adapted Cars

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Abstract

This study was carried out to increase knowledge about safety for drivers with disabilities. A questionnaire that focused on the driver's disability, the adaptive equipment, the use of the car, safety and accident involvement was sent to a random sample of persons with disabilities driving adapted cars. Spinal cord injuries were the most frequent diagnosis (30% of 793 answers) and lower limb disabilities were the most common functional restriction (over 75%). The drivers felt very safe and that they had a high level of confidence in the adapted car. They used the car for almost the whole distance travelled (90%), which illustrates how dependent this group is on the car for their mobility. About one out of ten drivers had been involved in an accident during the last 3.5 years, most of them with only material damage. The accident and injury risks of the target group did not differ significantly from the risks of drivers in general. A small number of accidents were attributed to problems with the special equipment in the car. The causes could be unfamiliarity with the controls, an adaptation that did not fully meet the needs of the individual or equipment that broke down.

Keywords

Adaptations, passenger cars, diagnosis, functional disabilities, driving habits, accidents, questionnaire.

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Introduction

Private driving provides an outstanding mean for independent mobility (Ranney & Hunt, 1997). This is even more pronounced for people with disabilities, for whom driving can prevent involuntary isolation, facilitate participation in work, education and social life. Subsequently, driving often lead to an increased quality of life. Public transportation can seldom substitute private car driving, specifically for those with severe disabilities. The mobility gained by driving can also have positive health effects and reduce public expenditure in the same way as depicted for the elderly (Hakamies-Blomqvist, Henriksson & Heikkinen, 1999).

So far much of the research concerned with drivers with disabilities has been focused on mobility issues (see e.g. (Haslegrave, 1986) and (Koppa, 1990)). However, all travel modes are associated with more or less risk. Safety is critical in order to achieve mobility objectives (Delén, 1999), but knowledge about safety for drivers with disabilities has been very limited, see e. g. (Turnbull & McKenzie, 1997). Safety concerns were also stressed by (Koppa, 1990) when he argued that preventive and protective safety in adapted cars should equal what standard production cars can provide. In a review of national and international research, it was pointed out that (the few) studies found often had methodological shortcoming, exposure was not accounted for and knowledge about different groups of disabled lacked (Transportforskningsdelegationen, 1980). TRL (Transport Research Laboratories) published more than one decade later two studies concerned with both safety and mobility aspects for drivers with disabilities assessed at Banstead Mobility Centre in the United Kingdom, (O'Toole & Simms, 1993; Simms & O'Toole, 1993). The results confirmed the importance of driving for this group of drivers and only few drivers reported problems in relation to driving. Furthermore, a similar age trend was seen as for drivers in general, with young drivers to be more accident-prone than middle-aged and older drivers were.

From analysis of crashes where at least one of the involved vehicles had to be towed away, (NHTSA, 1997) stated that vehicles with adaptive equipment were neither over- nor under-represented in crashes. According to (Haslegrave, 1986) drivers of adapted cars are less involved in crashes but no statistical analysis was provided. A Finnish study (Lääperi, Seppäläinen, Luoma-Aho & Alaranta, 1995) including 105 drivers with physical disabilities of which 60% were spinal cord injured (SCI) drivers found that these drivers had a slightly higher crash rate when exposure was not considered but lower if it was accounted for. They concluded that these drivers did not constitute a risk factor in traffic. This conclusion coincides with survey of current knowledge concerning drivers with SCI (Peters, 1998). A limited survey with drivers of joystick-controlled cars followed the same line of results (Östlund, 1999).

This study was initiated in order to fill the knowledge gap and to get a better understanding of the situation for a broader group of drivers with disabilities in Sweden and addressing both safety and mobility. It was aimed at describing the safety situation for drivers of adapted cars (accident involvement, subjective feeling of safety and confidence in the car), to obtain descriptive facts about the driver (type of disability, diagnosis), car (type of adaptive equipment) and their driving habits (mileage, experience). In case of low safety levels, counter-measures should be proposed in order to increase safety. Results from questions concerned with financial conditions and adaptive equipment have been presented briefly.
Material and Methods

Several ways to get in contact with the drivers were considered. The most ideal way would have been through either the driver licence register or the authority responsible for public subsidies to purchase or adapt a vehicle. But for secrecy reasons these registers were not accessible. Adaptation companies were also considered, but their customer registers were judged to be of too low quality. The solution was to indirectly establish a contact with the drivers through vehicle ownership.

The Swedish national vehicle register included in end of May 1999 about 4 million vehicles with a gross weight of maximum 3,500 kg of which 5,384 were registered as adapted for drivers with disabilities. This figure does not comprise all cars with adaptations, since simple ones as an extra accelerator or brake lever and a steering wheel knob do not require renewed vehicle registration and hence no changes are entered in the register in these cases. It can, by the number of vehicle grants, be estimated that there are in total more than 15,000 cars with adaptive equipment for the driver in Sweden (Peters, 2001). The difference between the two figures of adapted vehicles can also partly be explained by imperfect routines for vehicle registration inspections and follow-ups.

A systematic sample of every fourth vehicle registered as adapted was drawn, resulting in 1,325 vehicles (owners of several cars were only represented by one car and vehicles owned by driving schools were excluded). This sample size was judged to provide sufficient number of subjects in subgroups. A questionnaire was mailed to the owners of these vehicles in the summer of 1999. If the owner was not the driver, the owner was asked to hand the questionnaire over to the driver. By an initial question, it was possible to discriminate drivers not belonging to the target population from drivers that should answer the questionnaire. Since 271 vehicles in the sample (20 %) no longer were adapted (the register was not updated) or not driven by drivers with disabilities at the moment and another 16 cars were excluded by other reasons (owned by driving schools or adaptations companies or the owner had deceased), the number of potential vehicles in the target group was reduced to 1,038. Despite the season for the survey (summer), 76 % of these 1,038 owners/drivers answered the questionnaire after two reminders, which meant that data from 793 drivers of adapted cars were analysed. Fifteen of the respondents had recently given up driving, but where asked to complete the questionnaire and let the answers reflect the active period of car driving. After examining the proportion of drivers (vehicles) not belonging to the target group in relation to time of response, it was found that the later response, the higher proportion of non-adapted vehicles or drivers without disabilities among the respondents. Therefore a high proportion of drivers not belonging to the target group can be expected among the 245 vehicle owners not giving any kind of response. The response rate related to the real target group would therefore exceed 76 % with a less conservative estimate.

The questionnaire consisted of 31 questions divided in different sections. The respondents were initially asked to provide detailed descriptions of their diagnosis or impairment causes and functional disabilities. The following questions focused on travel habits. The next set of questions concerned the adaptive equipment in the car. The final section of the questionnaire addressed accidents and incidents. In view of reasonable correct remembrance of accidents, the start year of the period for the respondents' accident reporting was set to 1996 and the end point at the time for
receiving the questionnaire, forming a 3.5 years long period. At the end, space was provided for comments, which several of the respondents used.

Instead of mailing a questionnaire to drivers without disabilities (forming a control group), official statistics provided possibilities to compare with drivers in general concerning the use of the car and accident involvement.

Results

The results are representing only the respondents and hence are the figures unadjusted. To calculate a result to reflect the target population when the size of it is unknown or only rough estimates of it could be provided, was avoided.

The driver

The respondents in the present study were more often males, 62 %, and somewhat older, 51 years in average, compared to all driver licence holders in Sweden (55 % and 47 years, respectively). The most common diagnoses were spinal cord injuries (29.2 %) and polio (17.5 %), see table 1. The word "diagnosis" is used even if some of the items in table 1 describe what caused the disability, as traffic accident injury.

Table 1. Distribution of the answers to the question about diagnosis (n=777).

<table>
<thead>
<tr>
<th>Diagnosis</th>
<th>Number of answers</th>
<th>% of the respondents reporting the diagnosis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spinal cord injury</td>
<td>227</td>
<td>29.2</td>
</tr>
<tr>
<td>Polio</td>
<td>136</td>
<td>17.5</td>
</tr>
<tr>
<td>Traffic accident injury</td>
<td>118</td>
<td>15.2</td>
</tr>
<tr>
<td>Multiple sclerosis</td>
<td>97</td>
<td>12.5</td>
</tr>
<tr>
<td>Industrial injury</td>
<td>70</td>
<td>9.0</td>
</tr>
<tr>
<td>Muscular diseases</td>
<td>46</td>
<td>5.9</td>
</tr>
<tr>
<td>Injury caused by other physical violence</td>
<td>42</td>
<td>5.4</td>
</tr>
<tr>
<td>Tumour and cancer diseases</td>
<td>33</td>
<td>4.2</td>
</tr>
<tr>
<td>Rheumatism</td>
<td>32</td>
<td>4.1</td>
</tr>
<tr>
<td>Diabetes</td>
<td>28</td>
<td>3.6</td>
</tr>
<tr>
<td>Other congenital deformity</td>
<td>28</td>
<td>3.6</td>
</tr>
<tr>
<td>Spina bifida</td>
<td>27</td>
<td>3.5</td>
</tr>
<tr>
<td>Cerebral Palsy</td>
<td>26</td>
<td>3.3</td>
</tr>
<tr>
<td>Arthrosis</td>
<td>16</td>
<td>2.1</td>
</tr>
<tr>
<td>Other heart and vascular diseases</td>
<td>16</td>
<td>2.1</td>
</tr>
<tr>
<td>Short stature</td>
<td>15</td>
<td>1.9</td>
</tr>
<tr>
<td>Other skeleton and joint diseases</td>
<td>15</td>
<td>1.9</td>
</tr>
<tr>
<td>Stroke</td>
<td>14</td>
<td>1.8</td>
</tr>
<tr>
<td>Other neurological diseases</td>
<td>13</td>
<td>1.7</td>
</tr>
<tr>
<td>Osteogenesis imperfecta</td>
<td>11</td>
<td>1.4</td>
</tr>
<tr>
<td>Other internal medicine diseases</td>
<td>8</td>
<td>1.0</td>
</tr>
<tr>
<td>Other back troubles</td>
<td>7</td>
<td>0.9</td>
</tr>
<tr>
<td>Thalidomide injury</td>
<td>4</td>
<td>0.5</td>
</tr>
<tr>
<td>Other diagnosis</td>
<td>22</td>
<td>2.8</td>
</tr>
<tr>
<td><strong>Total number of answers</strong></td>
<td><strong>1051</strong></td>
<td></td>
</tr>
</tbody>
</table>
On average, the respondents ticked 1.4 of the diagnoses that were specified in the questionnaire. Of the single stated diagnosis, polio (21 % in this subgroup) was the most frequent followed by spinal cord injuries and multiple sclerosis (16 % each). The most common dual diagnosis was spinal cord and traffic accident injuries (32 % in this subgroup).

Table 1, however, can give only indicative information about the drivers’ physical limitations. Figure 1 was therefore included in the questionnaire. Approximately between 80 and 90 % (left respectively right foot and shank) of the respondents had impaired or no function in, or lacked one or both of the lower extremities. The corresponding proportion for trunk and upper extremities was 20-30 %. More details are shown in figure 1. Impairments in the right limbs were more common than in the left.

![Figure 1](image-url)  
*Figure 1. Percentage of all drivers (793) reporting impaired or no function in different parts of the body.*
Three out of four respondents always or occasionally used a wheelchair for outside transportation. Of these, 7% were seated in their wheelchairs while driving.

The car and the adaptation

The median age of the car was six years. About one out of ten of the adapted cars were of van model. A majority of the drivers, around 80%, had received some form of public subsidies for purchase and/or adaptation of the vehicle. It was very common with automatic transmission (90% of the cars, compared to 13% of all new passenger cars registered in the year of 1993 (Bil Sweden, 2002) and adapted steering, including augmented powered servo (69%). Combined hand controlled levers for braking and accelerating was found in 47% of the cars while 41% had a separate lever for braking and 38% had it for accelerating. 10% accelerated with left foot and 4% of all the respondents had an extended accelerator pedal. About 27% of the vehicles were equipped with an adapted seat for the driver while ramps or lifting devices for wheelchairs were found in 14% of the cars. Examples of simpler but still essential adaptations or equipment are a wheel knob or other handle attached to the steering wheel (26% of the vehicles), electrical powered windows (31%) and electrical powered rear windows (27%).

Using the car – experiences and habits

The importance of the car can be understood when considering how predominant the private car was as transport mode for all kinds of errands, see figure 2.

![Figure 2](image_url)  
*Figure 2. Frequency of car use by different types of errands. Percentage who answered the car "always" or "often" was used of those who gave an answer for respective errand.*
Of all distance travelled, 90% was carried out by car (to be compared with 65% for a Swedish person in general (Eriksson, 1999), mostly as a driver (77%) but also as a passenger (13%). More than half of the group, 53%, used the car 6 or 7 days during a normal week. The annual mileage for a disabled person in the investigated group, 13,508 km, was similar to the figure for the average driver in Sweden, 13,910 km (Konsumentverket, 1996). The main part of the distance was driven in daylight (74%) and 46% in rural area. The latter was a smaller proportion of driving in rural environment compared to the average driver in Sweden: 66% (Konsumentverket, 1996).

Half of the respondents (54%) held a driver licence before they became disabled. This group had long driving experience of non-adapted cars: 82% had been driving for more than 5 years, about 14% for less than 5 years but more than 1 year and hence 3% for a shorter period than 1 year. When considering the whole investigated driver group, a similar distribution of experience of driving adapted cars was seen.

**Safety**

A precondition for using the car and achieving mobility is that the driver has confidence in the car and the adaptive equipment. Therefore the questionnaire included two specific questions about experienced safety and confidence in the adaptation. The drivers did not find car driving as something particular unsafe. Seven out of ten drivers (71%) felt very safe when driving the car and 20% rather safe. Concerning confidence in the function of the vehicle and its adaptation, 70% had very big and 25% rather big confidence.

About 11% of the drivers with disabilities (or 84 drivers) had been involved in 97 accidents in total, including minor collisions, during the 3.5 years long report period (January 1996 to June 1999). In order to compare the number and outcome of the accidents reported in the questionnaires with official statistics comprising police-reported accidents for all drivers, accidents were divided into police-reported and not police-reported. This was possible since the respondents were asked whether the accidents were reported to the police or not, see table 2 and table 3.

**Table 2** Self-reported accidents with drivers with disabilities involved that occurred 1996 - June 1999 which were police-reported according to the respondents. Number of accidents by year and outcome.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Material damage only</td>
<td>6</td>
<td>7</td>
<td>10</td>
<td>1</td>
<td>24</td>
</tr>
<tr>
<td>Personal injuries</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>0</td>
<td>4</td>
</tr>
<tr>
<td>Total</td>
<td>9</td>
<td>9</td>
<td>12</td>
<td>1</td>
<td>31</td>
</tr>
</tbody>
</table>

*Up to June -99. **Driver with disabilities

As seen in table 2, seven out of 31 accidents led to personal injury. The number of accidents in 1999, up to June, was considerably lower than expected compared to previous years. An explanation to this, except for variation due to randomness, has not been found.
**Table 3** Self-reported accidents with drivers with disabilities involved that occurred 1996 - June 1999 which were not police-reported according to the respondents. Number of accidents by year and outcome.

<table>
<thead>
<tr>
<th>Severity of accident</th>
<th>1996</th>
<th>1997</th>
<th>1998</th>
<th>1999</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material damage only</td>
<td>11</td>
<td>12</td>
<td>26</td>
<td>8</td>
<td>57</td>
</tr>
<tr>
<td>Personal injuries</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>of which only the DD** was hurt</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>of which the DD** and other person</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>were hurt</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>12</td>
<td>14</td>
<td>27</td>
<td>10</td>
<td>63</td>
</tr>
</tbody>
</table>

In all, only 13 of the collisions (police reported in table 2 + not police reported accidents in table 3) lead to personal injury. The small number of accidents with personal injury made it difficult to generalize the findings or make comparisons between subgroups of drivers. Common circumstances of the collisions were when another driver hit the respondent’s vehicle from behind when he/she had stopped at an intersection, slippery roads or when other drivers neglected to give way to traffic coming from the right.

Due to changes in reporting routines, a comparison with data in table 2 with official statistics about accidents involving adapted vehicles is not feasible. Table 4 instead presents accident data for all vehicles.

**Table 4** All police-reported accidents involving vehicles with a gross weight of maximum 3,500 kg during the period 1996-1999. Number of accidents by year and outcome. Vägverket (2002).

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Material damage only</td>
<td>58152</td>
<td>47676</td>
<td>50927</td>
<td>21312</td>
<td>178067</td>
</tr>
<tr>
<td>Slight personal injury</td>
<td>10679</td>
<td>10567</td>
<td>10591</td>
<td>4894</td>
<td>36731</td>
</tr>
<tr>
<td>Severe personal injury</td>
<td>2419</td>
<td>2438</td>
<td>2548</td>
<td>1150</td>
<td>8555</td>
</tr>
<tr>
<td>Fatal accident</td>
<td>406</td>
<td>417</td>
<td>400</td>
<td>174</td>
<td>1397</td>
</tr>
<tr>
<td>Total</td>
<td>71656</td>
<td>61098</td>
<td>64466</td>
<td>27530</td>
<td>224750</td>
</tr>
</tbody>
</table>

*up to 30/6

Data about fatalities cannot be extracted from the questionnaires and therefore an estimation is based on the in-depth studies; one driver with disabilities is supposed to be killed during the 3.5 years long period. Together with traffic exposure reported in the questionnaire, risks could be calculated for drivers with disabilities. Travel data from a national inquiry representing the total driver population (Edwards, Nilsson, Thulin & Vorwerk, 1999) and official statistics from The Swedish National Road Administration (Vägverket, 2000) provided comparable data for drivers in general. Accident risk and risk for a fatal or injury accident during the 3.5 years long period are shown in figure 3.
The risks did not differ significantly between drivers with disabilities and the general driving population. A 95 % confidence interval for the relative risk of accident involvement, 0.85/0.98, could be calculated to 0.61 - 1.23, hence it can not be rejected that the quota could be equal to 1. The low number of accidents in the disabled driver group contributes to the non-significant results.

Three different types of accident causes were identified as related to the adaptation equipment:

a) The driver was unfamiliar with the equipment (3 cases)
b) The adaptation was not carried out enough individually (2 cases)
c) The equipment broke down (4 cases)

An example of the first type was when the driver accelerated instead of braked in a car with new equipment. Requiring a break force in an emergency situation, which the driver cannot produce, illustrates the second type. Three of the four cases with technical problems dealt with combined levers for braking and acceleration that broke down. No severe accidents were reported as a consequence of technical problems, but personal injuries were reported due to the first two circumstances. A recent investigation of different devices for adapting the braking system to drivers with disabilities by MIRA (The Motor Industry Research Association) revealed that with a partial braking system failure four out of five mechanical system were unable to provide sufficient braking performance (Curry & Southall, 2002). The Swedish National Road Administration has also identified technical problems with adaptive equipment, specifically concerning improper installation (Petzäll, 2002). A manoeuvre test with joystick-controlled cars (Östlund & Peters, 1999) revealed some driver control problem related to the technical implementation of joystick systems.

Even if a vast majority felt safe and reported no problems with the car or the adaptation, measures to increase safety were proposed by the respondents. One example was that more frequent contacts between authorities involved in the complicated procedure to adapt a vehicle would increase the possibility to get special equipment that works satisfactory. A more flexible system of subsidies to facilitate continuous adaptations in case of progressive diseases (e. g. rheumatism), thoroughly
fastening of wheel chairs while driving (including empty ones) and better designed parking lots for drivers with disabilities are other examples.
Discussion and conclusions

The primary objective with this survey was to increase the knowledge about drivers with disabilities, specifically address safety aspects of adapted cars and furthermore, to overcome deficiencies observed in previous surveys. This objective was successfully achieved and specifically it should be noted that the response rate was very high. However, the results need to be considered in a wider frame of reference and there are some problems that need to be commented.

One initial problem, which was faced when planning the present study, was how to define drivers with disabilities and thereafter, how to reach them. The chosen sampling frame, the vehicle register, did not include simple types of adaptations. The reader should therefore have in mind that the findings are only applicable to a subgroup of drivers of adapted cars, however an important group with respect to the severity of disability. A relatively large proportion of the respondents were drivers with spinal cord injuries, close to 30%. This is probably one of the largest or even the largest group of drivers of adapted cars.

Sufficient safety is a precondition for achieving the mobility objectives. Thus, the current survey addressed safety in terms of both risk (accidents and incidents) and subjectively experienced safety. The results give no reason assume that drivers of adapted cars in general are at higher risk than other drivers. Furthermore, the results indicate that drivers of adapted cars feel, subjectively, safe as drivers. Are these results sufficient to conclude that there are no problems? Risk or threat as a regulating factor explaining driving behaviour has been proposed and applied in several motivational models of car driving (e.g. Fuller, 1984; Näätänen & Summala, 1976; Wilde, 1982). However, this approach has been heavily criticized (e.g. Sanders & McCormick, 1993) and found insufficient (e.g. Michon, 1989) to explain driver behaviour and specifically driver adaptation (van Winsum, 1996). Despite this it can be argued that the driver’s experience of risk and safety can play an important role for the overall mobility. Michon (1985) developed a model in which driving is structured in three hierarchical levels: strategical, manoeuvring, and control. The criticism of risk-based behaviour concerned primarily the behaviour on the control and manoeuvring level, actual car handling and traffic rule following. However, behaviour at the strategical level includes more general and long term behaviour as selection transport mode e.g. driving on your own or using special transport services. If the risk is experienced as too high on the strategical level it might restrict the use of the adapted car. The respondents’ proposals for improvements and the problems observed by (Östlund & Peters, 1999), the SNRA (Petzäll, 2002) and MIRA (Curry & Southall, 2002) give reason to believe that the situation is far from satisfactory even if this is not shown in the accident statistics. It should also be considered that there are drivers who give up driving because they were provided with wrong or insufficient adaptation or because they have no confidence in the car and its adaptation. One of the fifteen non-active drivers in this study was a learner driver who had faced problems with the adaptation during the learning period and subsequently decided to temporarily interrupt the learner driver efforts. The need for sufficient training with the adaptive equipment should not be underestimated especially considering that there might be a need to learn new automated behaviour (Peters, 2001). There is a need to investigate this further and address people who gave up driving or were never successful in getting a licence.

The used method could be criticized. Besides the unreliable way to ask about accidents experienced (memory problems, unwillingness to describe certain accidents), the respondent was
also asked to distinguish between police reported and not police reported accidents. The presence of a policeman at the crash site is not always resulting in a police report, something that the respondents may believe. However, in a situation with incorrect data in the vehicle register, the chosen method is regarded as the best to obtain accident statistics about drivers with disabilities. With the common coding system for driving licences in the European Union (introduced in 1996 in Sweden), a more detailed picture can be obtained of not only type of disability but also type of equipment in the car needed for the driver. It is believed that the most eligible way in the future to get reliable statistics about traffic safety for drivers with disabilities is to combine driving licence data with accident data. In that case, a lot of the problems discussed previous will be avoided.

Concerning the respondents' suggestions for improvements e.g. better communication between authorities it should be noted that this problem has been addressed several times both on a national and international level (Fulland & Peters, 1999). Furthermore, the respondents’ comments together with other observations of problems related to vehicle adaptations, as discussed above, points to the needs of improved support to drivers with disabilities. For instance, a mandatory adaptation evaluation could be used to verify that an adaptation compensates for the driver’s disabilities and that the driver has received sufficient training with the adaptation (Peters, 2001).

This survey showed that the drivers with disabilities in adapted cars did not constitute a traffic safety risk different from drivers in general; similar to what was found in (Lääperi et al., 1995). Rather a bit lower risk considering that drivers with disabilities are more vulnerable due to their impairments. Their ability to fulfil their transportation needs on their own at such a high level as indicated by this survey substantially contributes to improved quality of life (one of the respondents expressed it concisely: "The car is my legs") and beyond that even reduced public expenditure. Thus it seems like the current regulations for drivers with disabilities should not be more restrictive rather it can be argued that a more generous regulation and support should be applied. However, there is a need to further investigate the situation and then focus should be directed more to those who have not been able to achieve an independent mobility as drivers of adapted cars.

**Acknowledgement**

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Joystick versus conventional driving controls

Joystick versus conventional driving controls

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Abstract

Joystick controlled vehicles for disabled drivers are not common. Since a joystick differs fundamentally from conventional primary controls, studying joystick control can reveal several critical issues concerning alternative primary controls and drive-by-wire technology. A joystick combines steering and speed control in one single lever. In a manoeuvre test with joystick-controlled cars, interference between steering and speed control and difficulties in performing fast and accurate steering were observed.

Background

Electronic components have the potential of replacing mechanic/hydraulic components of the primary control systems of the car. The use of electronic components allows for flexible control design and placement. For over a decade, joystick controlled cars have been a reality for drivers with disabilities (Östlund, 1999). Car adaptation companies are to some extent aware of potential risks and deficiencies with current joystick-controlled cars. A joystick can be difficult to handle and is therefore considered a last adaptation alternative. In December 1998, a manoeuvre test was conducted to study the Human Factors aspects of joystick control for drivers with disabilities (Östlund & Peters, 1999). This study was the first to focus on joystick-controlled cars for drivers with disabilities.

Joystick design and control-characteristics

The joystick is used to control speed and steering. The joystick car drivers mostly lack strength and hand mobility, and for that reason the joystick is small and mainly controlled by small finger movements and hand rotations. The joystick angular range of motion is 1/30 of that of the steering wheel. The obviously resulting precision/range problem is commonly solved by a speed-dependent downscaling and filtering of steering commands. The filtering and system limitations result in time lags. As a consequence, it may be difficult to perform very fast and large steering manoeuvres, and there is not a correspondence between joystick and steering wheel at all times.

The joystick does not facilitate separate steering and speed control; interference may occur between speed control and steering control (Östlund, 1999; Milberg, 1979). The joystick seems to be more suitable for a single two dimensional control task (like positioning a cursor on a screen) than two separate one dimensional control tasks (like adjusting chrominance and luminance of a display).

Current joysticks provide no haptic feedback but a centring spring force. As a consequence, much of the information normally transmitted to the driver via steering wheel and brake pedal is eliminated. The driver does not "feel" the road as with conventional controls, and that is why vehicle state awareness is reduced; disturbances and slippery roads can be hard to detect and compensated for.

**The manoeuvre test at Mantorp Driving Court**

*Objectives and Method*

Three driving manoeuvres were performed by five experienced joystick car-drivers. They drove their own joystick-operated cars. Also a control group of non-disabled drivers drove the test with a conventional car. The test mainly focused on steering precision and interference.

The manoeuvres in the test were (1) firm and controlled braking on straight road, (2) firm and controlled braking in narrow curve, and (3) double-lane change. See figure 1.

*Figure 1. (Top down) Firm controlled braking on straight road; firm controlled braking in narrow curve; and double-lane change.*

The objective of the first and second manoeuvre was to study brake performance and brake/steering-interference. The objective of the double lane change was to
investigate the possibilities to perform a fast lane change. Expected results were interference, unstable lateral control, and difficulties to steer fast enough.

**Results and conclusions**

The main result from the braking manoeuvres (test 1 and 2) was that corrections and unintentional changes in steering resulted in changes in brake force as well. This did not happen for the control group.

The following was observed in the double lane change: (1) The joystick drivers had great difficulties managing the manoeuvre in 45 and 50 km/h, but also to some extent in 40 km/h. The joystick drivers hit cones in almost every try. The control group had no observable difficulties in managing the lane change in any of the three speeds. (2) Interference occurred for the joystick drivers. Especially during steering manoeuvres, firm unintentional brake force could be applied.

The joystick drivers were unable to steer their cars with sufficient speed and magnitude. This shortcoming was either due to driver- or system limitations. The test leader’s opinion was that it was a combination of both. Lateral body support and the arm support for the joystick drivers may have been insufficient and thus affected the performance. This was however not evaluated. The interference that occurred in the lane change and the narrow curve did not only depend on false-directed joystick movements, but also on joystick movements induced by body movements, in turn caused by car movements.

**Alternative design**

*Active feedback* is artificial feedback based on system reactions on input and disturbances. Active feedback could give the driver adequate information on road surface and front wheel steering angle, and could also compensate for system induced time lags. This would increase the driver-vehicle control loop bandwidth (Korteling & van Emmerik, 1998; Merhav & Ya’cov, 1976; Tunberg, 1991). A redesign of the joystick should be made to separate steering from braking/accelerating control. It is further of high importance that the driver is firmly fixated in relation to the car and joystick, so that car-movements cannot be induced to the joystick through the driver.

**References**


Joystick Controlled Driving for Drivers with Physical Disabilities - A Driving Simulator Experiment

1 Manuscript for publication.
Joystick Controlled Driving for Drivers with Physical Disabilities - A Driving Simulator Experiment

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Abstract

A driving simulator experiment was conducted with the objective to investigate two salient design features, control coupling and feedback, of four-way joystick systems. The tested joysticks were aimed to be used in passenger cars by drivers with severe disabilities for steering, braking, and accelerating. Previous research with cars adapted with joystick controls have shown that time lags, control interference, and lack of feedback made these systems hard to learn and difficult to use. Four different joystick designs were developed and tested by combining two factors: coupled/uncoupled control and active/passive feedback. Time lags were made similar to what is found in the steering system of standard cars. It was expected that uncoupling and active feedback would provide improved control, less workload and facilitate learning to drive. Sixteen experienced drives with tetraplegia participated in the experiment. The drivers were all paralysed in their legs and used their upper limbs to drive their cars. The driving task consisted of both driving on a road and a double lane change manoeuvre. All subjects drove with all four joystick designs. Even if the participants were diagnostically homogenous they were functionally diverse which contributed to a large variation in data. Thus, the analysis was done both for the total group and for two separate groups of equal size depending on their right arm and hand function. It was found that uncoupling of lateral and longitudinal control provided better control and imposed less workload. This was specifically true for drivers with better hand and arm function. Active feedback was experienced as positive together with the uncoupled control by the same group of drivers and provided better control during the lane change manoeuvre. However, the drivers with less arm and hand function were in more favour of passive feedback. It even seemed like the active feedback was disturbing to them. The reduction of time lags contributed to make it easy to learn to drive with the tested joysticks. Active feedback and uncoupling did not seem to influence learning. It was finally concluded that reduced time lags, uncoupled lateral and longitudinal control and active feedback have a potential to improve control and facilitate driving with a four-way joystick but the adaptation needs to be individually adjusted.

Keywords: joystick, adaptation evaluation, driving performance, driving simulator, spinal cord injury.
Introduction

A person with locomotor disabilities can hold a driving license only if the disabilities can be compensated for by prosthesis or vehicle adaptation according to the European driving license directive 91/439/EEC (EEC, 1991). However, adaptations are seldom evaluated with respect to the compensatory requirements (Fulland & Peters, 1999). Thus, there is a need for an evaluation that can ascertain that the driver is provided with an adapted vehicle which will make driving equally safe as for a driver without disabilities (Peters, 2001c).

The emerging control-by-wire technology in cars provides a potential to develop driving controls, which can be used to compensate for even severe locomotor disabilities e.g. four-way joysticks (Östlund, 1999). Today, there are some commercially available joystick systems, which were specifically developed for drivers with very limited strength in their arms and hands (Östlund, 1999). However, these systems are hard to learn and difficult to use (Strano, 1997, Östlund, 2002). Furthermore, there are few regulations, standards, and guidelines that apply to vehicle adaptations (Fulland & Peters, 1999; Pierce, 1997; Strano, 1997; Veenbaas & Brekelmans, 1996) and specifically there are no guidelines concerned with joystick control systems.

A manoeuvre test was conducted on a closed track with the aim to study lateral and longitudinal control of joystick-controlled cars adapted to drivers with severe disabilities (Östlund & Peters, 1999). The test included the following three manoeuvres (1) firm and controlled braking on straight road, (2) firm and controlled braking in a narrow curve, and (3) double-lane change. The three manoeuvres were carried out at three different speeds (40, 45 and 50 km/h). The participants drove their own joystick controlled cars, which were individually fitted. They were experienced with the cars and the joystick systems. It was found that they had difficulties in performing smooth and fast stops. Braking in a curve turned out to affect steering control. Finally, in the double lane change manoeuvre it was found that it was difficult to control steering with sufficient speed and magnitude. The conclusions drawn were that the tested joystick systems had some functional deficiencies:

- Time lags
- Lack of feedback
- Interference between lateral and longitudinal control

Cognitive Systems Engineering (CSE) (Hollnagel, 2002a, 2002b; Jagacinski & Flach, 2003) can be used to model driving in order to understand the observed problems. Driving can be described as a control loop with three phases: perception, decision, and action. Driving speed will determine the time available to complete the control loop. When speed is low there will be ample time to plan or anticipate control actions but as speed increases the time frame will decrease and driving will become more reactive or compensatory. Driving is a task that is carried out on more or less distinct hierarchical control levels (Michon, 1985; Ranney, 1994). The Extended Control Model (ECOM) (Hollnagel, 2002a) distinguished four levels of control: controlling, regulating, monitoring, and targeting. Furthermore, the driver’s control of the car is guided by a mental model, which will be revised according to the outcome of control actions (feedback). This guiding and feedback mechanism connects the hierarchical control levels.

Time lag problem had to be handled by the previously described joystick drivers on a high cognitive level and in an anticipatory way. In ECOM terms this means that this problem had to be dealt with on a targeting and monitoring level. The drivers had to plan how to move the
lever in order to compensate for the time lags and maintain control in the double lane change. It is very difficult to model time lags and it will take a long time and experience to develop a sufficiently good mental model to guide the control (Jagacinski & Flach, 2003). The interference problem mainly affected the driver’s control on the regulating and monitoring levels. The drivers probably had a mental model of how their joysticks worked but it was not sufficient in order to know what direction to move the lever in order to brake without affecting steering control. They had to regulate and monitor their control actions closely in order to adjust the joystick motions. This type of manoeuvre requires both anticipatory and compensatory control. It was also observed that the drivers compensated performance decrements by driving slowly in the curve. Finally, the lack of tactile feedback when braking mainly influenced the driver’s control at the control level in the ECOM model. The drivers were not able to adjust the force applied on the brake lever in order to make a soft stop. It was concluded that the feedback they experienced, as whole-body g-forces and visual cues were not sufficient to regulate the force applied to the brake. In conclusion, it seemed like the observed problem could be attributed to design imperfection in the tested system.

The results from the manoeuvre test were used to formulate hypotheses for this experiment. The aim was to further investigate two salient design features of joystick systems: control coupling and feedback. Time lags were considered to be such a severe and undesired design flaw that they were virtually excluded by designing the systems to be tested to behave as the ordinary controls in a standard production car. The observed problem with interference in the manoeuvre test was addressed with an alternative design which more clearly separated lateral and longitudinal control compared to conventional joystick systems. This design, called uncoupled control, was compared with a conventional joystick design, called coupled control. Lack of feedback was the third problem observed. Thus, feedback was a design feature tested in the experiment with two alternatives passive and active feedback. Four different joystick designs were derived by combining the two design features, control coupling and feedback. Four hypotheses were formulated:

1. **Uncoupled control** was expected to provide better control to driver, be more comfortable (less workload) and be more preferred by the drivers compared to the coupled control.

2. **Active feedback** was expected to provide better control to driver, be more comfortable (less workload) and be more preferred by the drivers compared to passive feedback.

3. **Uncoupled control and active feedback** was expected to result in best performance, be most comfortable, and to be most preferred by the drivers of all four designs.

4. **Learning** was expected to be easiest with uncoupled control and active feedback.
Method

A two-by-two factorial, within-subjects design was used for the experiment. Sixteen drivers participated in the experiment. All subjects drove under all four conditions. The order of conditions was counterbalanced. Within-subjects design was used in order to limit nuisance effects due to individual differences caused by their impairments. In fact, there was a third factor, learning, as the driving task was repeated twice for all four joystick designs.

Participants

The selection of participants was based on discussions with both specialists at a rehabilitation clinic and a vehicle adaptation company with long experience of joystick adaptations. Currently, there are about 20 drivers of cars adapted with joystick systems in Sweden. These drivers have considerable physical disabilities. However, they have sufficient fine motor ability to drive with a joystick. All of them drive sitting in their electric wheelchairs. However, it was not possible to adapt the driving simulator in order to accommodate these drivers. Drivers with a traumatic Spinal Cord Injury (SCI) at cervical level have more or less impaired motor and sensory functions in their upper limbs and are usually paralysed in trunk and lower limbs. It was decided that drivers with SCI at cervical level (C4-C7) were a suitable group for the experiment. The primary motive to this choice was that these drivers constitute a group of potential drivers of joystick controlled cars. Second, drivers with SCI are the most frequent drivers of adapted cars in Sweden (Henriksson & Peters, 2004). Third, drivers with SCI usually have well defined functional sensory and motor disabilities. The following inclusion criteria were used when recruiting participants:

- Spinal Cord Injury at level C4 – C7
- Sufficient fine motor ability in right arm and hand
- No or minimal risk of spastic contractions or jerky motions
- No perceptual (visual, hearing) impairment
- No cognitive impairment
- Experienced as driver of adapted cars

The experimental group consisted of 15 male and 1 female drivers with an average age of 35.5 years. Their average annually driven distance was approximately 25,000 km which was almost double the length driven by Swedish drivers in general (13,910 km) and drivers of adapted cars in general (13,508 km) (Henriksson & Peters, 2004). See Table 1 for details.

The level of injury and ASIA (American Spinal Injury Association) motor scores for right hand/arm were used to describe the participants’ functional impairment (Table 1). The level of injury will give a rough idea of the extent of the functional impairment but it is not sufficient to describe the abilities. The ASIA motor scores can be used as measure of the residual motor abilities in the limbs. The higher score the better is the function. The scores for the right arm and hand was most critical as they used this limb to control the joystick. Five functions are assessed for upper limb ASIA motor scores: elbow flexors, wrist extensors, elbow extensors, finger flexors, and finger abductors. A five-graded scale is used to score the functions. Thus, full arm and hand function would give a score of 25. According to Table 1 were the motor scores different even for injuries located at the same level. A lesion can be
more or less complete. A complete lesion will rule out all sensory and motor function below this level while incomplete lesions can provide varying degrees of function.

Table 1 Summary of descriptive data for the participants

<table>
<thead>
<tr>
<th>Driver</th>
<th>Age (years)</th>
<th>License (year)</th>
<th>Conditioned license (year)</th>
<th>Annual distance (1000 km)</th>
<th>Level of injury</th>
<th>ASIA Motor score right</th>
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<tr>
<td>1</td>
<td>60</td>
<td>40</td>
<td>18</td>
<td>22.5</td>
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<td>24</td>
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<tr>
<td>2</td>
<td>53</td>
<td>34</td>
<td>28</td>
<td>15</td>
<td>C6-C7</td>
<td>25</td>
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<td>3</td>
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<td>9</td>
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**Driving simulator**

A dynamic, high fidelity, moving base driving simulator was used (Nordmark, 1990). The vehicle was modelled in a computer system and a moving base system was used to simulate accelerations in three directions through roll, pitch and linear lateral motions. A visual system presented the external scenario in the form of computer-generated graphics on a screen (120° x 30°), 2.5 meters in front of the driver. A sound system generated noise and low frequency sound that resemble the internal environment in a modern passenger car. A vibration system simulated the sensations the driver experience from the contact between the road and the vehicle. A temperature system controlled the air temperature in the driver's cab. A number of validation studies have successfully been performed in this simulator (Törnros, Harms, & Alm, 1997). These studies showed that the moving base system (pitch ± 24°, roll ± 24° and lateral ± 3.5 m) was important for the experienced reality and external validity, specifically the lateral motion was crucial to generate realistic forces on the driver. The motion base feature was considered critical for this experiment as much attention was focused on the driver’s lateral control. The short time delay, 20 ms, has proved to be vital in order to limit the occurrence of motion sickness. The car cab was a Volvo 850. However, the modelled car was a Volvo V40 i.e. front wheel driven with automatic gearbox.

**The joystick system and other adaptations**

A joystick system by Immersion Corporation was used as the central unit for the four joystick designs tested. Two physical designs were used to realise the two versions of control
coupling. The *coupled* control joystick was realised by replacing the ordinary lever with a forklike grip developed for drivers with tetraplegia (Figure 1 a). The joystick with *uncoupled* control was implemented by modifying the joystick with a mechanical device that transformed the radial speed controlling motion into a linear longitudinal motion (Figure 1 b). The driver’s hand was placed in a tri-pin grip that could be adjusted to fit different hands.

![Figure 1](image)

Figure 1 The coupled (a) and uncoupled (b) joystick system. Arrows indicate how steering, accelerating and braking commands.

The joystick system was equipped with both sensors and actuators which were used to monitor the driver’s control commands and to provide force feedback to the driver. The joystick was controlled by a C++ program running on a dedicated PC, which communicated with the driving simulator’s computer via a CAN bus connection. Passive feedback was realised as centring spring forces in the joystick. Thus, if the driver released the joystick it would move to a neutral position. The centring forces were present for the passive and active feedback condition. With active feedback, steering wheel momentum and damping effects were fed back as lateral forces in the joystick. Steering was position controlled and there was a linear relation between lateral joystick angle and wheel angle. The joystick’s range of motion was ± 38 degrees which was not much compared to an ordinary steering wheel ± 630 (3.25 revolutions). Thus, there is a great risk that joystick steering becomes very sensitive. Thus steering output was down scaled from 40 km/h. Furthermore, the steering algorithm compensated for the vehicle speed dependent progressive under-steering. Steering commands were also somewhat damped (4 Hz low pass filtered) to simulate the effect of a steering servo. Speed was controlled with longitudinal forces on the joystick. A backward force was linearly transferred to an accelerator *position*, and a forward force was linearly transferred to a *force* on the brake pedal. Reactive forces were fed back to the lever. The longitudinal feedback was identical for the passive and the active feedback conditions.

The steering wheel was removed in order to facilitate ingress and egress. The original driver’s seat and standard safety belt was used. An extra postural support belt was available if needed. The joystick was positioned to the right of the driver approximately where the gear selector is normally placed. The driver placed his/her arm in an adjustable arm support.

**The driving task**

The driving task was designed to include both simple and demanding situations, driving on a rural road and a double lane change manoeuvre. Driving on rural road was used to study
normal driving behaviour. While, the lane change manoeuvres were considered to be demanding and thus used to study driving performance. The distinction between behaviour and performance was made according to Evans (1991). The test route was a 20 km long two-lane rural road with smooth vertical and horizontal curvature. The lane width was 5.25 m including a 1.7 m wide hard shoulder. Driving conditions were comparable to a dry summer asphalt road i.e. high friction. Sight conditions corresponded to a slightly hazy day. Signed speed limit was 90 km/h. There were randomly oncoming passenger cars appearing at low frequency. Twice, the participants caught up with a lead vehicle. The drivers were instructed to follow at a safe distance. The speed of the lead car varied randomly for 3 km and then the car moved over to the hard shoulder to let the test driver pass. Driving on the rural road was used to study the drivers’ lateral control. The car-following situations were aimed to study the longitudinal control. The double lane change manoeuvre was designed according to ISO/TR 3888 (ISO, 1999). The lane-change path was outlined with 9 pairs of amber cones (see Figure 2). The width in the three sections increased with 10 percent starting with 2.19 m.

**Figure 2** Double lane change manoeuvre. Lane width in section A: $1.1 \cdot \text{vw} + 0.25$, in section B: $1.2 \cdot \text{vw} + 0.25$ and in section C: $1.3 \cdot \text{vw} + 0.25$, where $\text{vw}$ is the width of the car (1.76 m) (ISO, 1999).

**Measures**

Three types of measures were used: driving behaviour and performance, physiological and subjective measures.

**Driving behaviour and performance measures**

Free driving (no car following), car following, and lane change manoeuvre were analysed separately. Several measures were used to analyse the driving behaviour and performance (Table 2). TTC (Time-To-Collision) and TH (Time Headway) were used as a time based measure of longitudinal safety margin (van der Hulst, 1999; van Winsum, 1996). TH was calculated as the headway distance to lead vehicle divided by the speed of the lag car. Headway distance was defined as the distance from the lag car’s front bumper to the lead cars rear bumper. TTC was computed as the headway distance divided by the speed difference between the two vehicles. Standard deviation of speed during the lane changes were used to analyse the longitudinal control in the lane change manoeuvre. Mean lateral position and standard deviation of lateral position (SDLP) was used to evaluate the driver’s lateral control. Increased SDLP was regarded as degraded lateral control. Time-to-line-crossing (TLC) was used to analyse the driver’s lateral control. TLC is defined as the time left until a moving vehicle crosses either side of the lane boundaries (white lines) under the assumption that the vehicle continues along the same travel path (i.e. constant heading angle) with the current momentary motion (i.e. speed) (Godthelp, 1986; Godthelp, Milgram, & Blaauw, 1984). TLC data were calculated using an approximation (van Winsum, Brookhuis, & de Waard, 2000).
Table 2 Summary showing how different driver behaviour and performance measures were used in the analysis

<table>
<thead>
<tr>
<th>Measure</th>
<th>Free driving</th>
<th>Car following</th>
<th>Lane Change Manoeuvre</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>General performance/behaviour</strong></td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>- Speed (km/h)</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>- Collisions</td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>- Cones hit</td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td><strong>Longitudinal Control</strong></td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>- Headway Distance (m)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Time Headway (s)</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Time to collision(s)</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Lateral Control</strong></td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>- Mean lateral position (m)</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Std lateral position (m)</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>- Time to Line Crossing (s)</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>- Number of line crossings</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td><strong>Joystick Control</strong></td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>- Std lateral motions (degrees)</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>- Std longitudinal motions (degrees)</td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>- Joystick lateral reversal rate</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>- Correlation between lateral &amp;</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>longitudinal joystick speed</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Two specific measures were used to analyse how the drivers moved the joystick. Joystick lateral reversal rate was defined as the total number of times the direction of joystick motions was changed per kilometre. Correlation between lateral & longitudinal joystick speed was calculated for each lane change as the correlation between the absolute values of the lateral and longitudinal joystick angular speed. This measure increases as longitudinal and lateral joystick angle are changed simultaneously. Thus, it was used as a measure of interference during the lane change as the manoeuvre should be carried out as a steering task with constant speed.

**Physiological measures**

ElectroMyogram (EMG) and ElectroCardioGram (ECG) were used to measure and analyse physical and mental workload. The Deltoid Anterior (upper arm) and Trapezius (shoulder) muscles were used to operate the joystick (Sprigle, Morris, Nowachek, & Karg, 1995). EMG was used to measure muscle load (Birch, Juul-Kristensen, Jensen, Finsen, & Christensen, 2000). Baseline EMG were individually measured as the participant extended the right arm straight out in front (Deltoid) and straight out to the side (Trapezius). The muscular loads were calculated as percentage of the baseline loads per individual. ECG data were used to calculate Inter-Beat-Interval (IBI) and Heart rate variability (HRV). IBI was used as an indicator of changes in arousal level and HRV as a measure of mental workload (Kalsbeek & Ettema, 1963; Mulder, 1988; Wilson, 1992). The 0.1 Hz component of the HRV was used in the analysis (Egelund, 1982; van Winsum, Van Knippenberg, & Brookhuis, 1989).
Subjective measures

Three questionnaires were used to capture the drivers’ subjective opinions during the experiment. The three questionnaires covered the following topics:

- Subjective rating of performance, workload, and joystick control aspects
- Comfort, stability, pain, joystick preferences, simulator realism and sickness
- Difficulty of manoeuvre task, joystick preferences

Procedure

Background data was collected before the participants arrived. The participants were given written and spoken information about the experiment as they arrived. However, they were not told about the differences between the tested joystick systems. Electrodes were attached and connected to the recording system. The drivers entered the simulator with help of a wheelchair lift and were assisted to find a stable and comfortable seating. All drivers drove at two occasions. One occasion included two consecutive test sequences during which the driver drove with one of the four joystick designs. Each sequence started with a training drive which was identical to the experimental drive i.e. a 20 km rural road driving and three lane change manoeuvres. Training was followed by two successive experimental drives (driving on the road and three lane change manoeuvres). This procedure was followed for all four joystick designs. The drivers were told to drive as they would normally do on a similar rural road and to be aware of the speed limit (90 km/h). Before the manoeuvre test the drivers were instructed to drive between the cones at a constant speed of 50 km/h and without hitting any cones. They drove a short distance before entering the first cone pair during which their speed was clearly displayed on the front screen. The speed feedback was turned off as they passed the first pair of cones. The three questionnaires were administrated at the end of each session, each occasion, and last occasion. All drives were video recorded. Running one occasion with two driving sequences took about 3 hours and sometimes more. The participants were paid 1000 SEK and travel expenses.

Statistical Analysis

Individual means were calculate for each of the four joystick configurations, for each of the two repeated drives per condition (8 per driver) and finally for each of the six lane changes included in every sequence (24 per driver). Individual and group means were calculated and analysis of variance (ANOVA) was used to analyse data. A further analysis was also done considering the functional difference within the group of drivers. Even if all participating drivers had a spinal cord injury classified as tetraplegic they were quite different in their arm and hand function as indicated the ASIA scores (see Table 1). The ASIA motor scores for the right arm/hand were used to form two groups equal in size (8 + 8). The first group was made up of drivers with ASIA motor scores equal to 15 or below and the other consisted of those with scores over 15. A significance level of 5 percent was applied in the statistical tests. The statistical analysis was done with Excel and SPSS 11.0 for Windows. Significant differences are indicated with F, p and ω² (power) values form the analysis of variance.
Results

The presentation of the results was divided into five sections: rural road driving, lane change manoeuvres, physical and mental workload, drivers’ opinion, and effects of learning. The analysis was based on means for all 16 participants if nothing else is mentioned.

**Driving behaviour - rural road**

The analysis of driving behaviour was split in two parts: free driving and car following. Free driving was defined as driving without any lead vehicle in sight. Approximately half the distance, 10.6 km of 20 km was considered as free driving. The analysis was based on 21.2 km driving as each driver drove twice. No collisions occurred. Speed data were used to analyse longitudinal control. The average speed was between 92.9 to 94.1 km/h for the four conditions. Speed variation in terms of standard deviation was ranged between 4.23 to 4.75 km/h. There were no significant differences between the four conditions with respect to speed control. Several measures were used to analyse lateral control. In general, the participants drove more to the right than to the left e.g. they crossed the right lane marker more frequently than the left (6 vs. 0 crossings/km) and the TLC\textsubscript{min} values right were lower compared to left for all four joysticks (mean TLC\textsubscript{min} right 3.6 vs. left 5.3 s). There was one significant difference in terms of lateral control. The participants drove 6 cm more to right with the coupled joystick (2.19 vs. 2.13 m, F(1,15) = 4.57, p < 0.05 (.5)). The lane width was 3.55 m which meant that the lateral position would be approx 1.78 when driving in the middle of the lane. Thus, the participants drove approx 40 cm to the right of the middle of the lane with the coupled joystick. There were no significant differences between the four joystick designs with respect to SDLP or TLC\textsubscript{min}. Joystick control was analysed separately. It was found that the joystick lateral reversal rates were higher with the coupled joystick compared to the uncoupled (149 vs. 109, F(1,15)=84.58, p< 0.05 (1.0)) and there was a significant difference between active and passive feedback (132 vs. 126, F(1,15)= 18.16, p < 0.05 (0.98)). However, this did not result in any corresponding significant differences in the standard deviation of lateral motion in the joystick lever. No significant interactions were found.

When analysing the data it was observed that several drivers frequently crossed the right lane marker and drove on the hard shoulder. The hard shoulder was rather wide (1.7 m) and this could have encouraged the drivers to drive more to the right. Thus, two alternatives to the right lane marker were defined: the right road edge and a virtual line that was derived by mirroring average distance to the centre line for free driving. However, this extended analysis of TLC\textsubscript{min} data did not reveal any significant differences between the four joystick designs.

The 20 km rural road driving included two car following situations, which lasted for 3 km. Both lateral and longitudinal measures were used to analyse driving behaviour. No collisions occurred during car following or overtaking. The drivers were rather careful and maintained relatively long distances to the lead vehicles. The average mean distance to the leading vehicle was 47 m. Averages for min TH, min TTC and mean TTC were 2.5, 27 and 56 seconds respectively. The analysis of longitudinal control did not reveal any significant differences with respect to joystick design. Lateral control data conformed rather well to what was found for free driving with two exceptions. The difference between coupled and uncoupled joystick in lateral position was not found. Furthermore, there was a significant difference in min TLC\textsubscript{min} left. Active feedback led to lower min TLC\textsubscript{min}, 1.5 vs. 1.7 (F(1,15) = 6.03, p < 0.05) compared to passive. Finally, there was significant difference with respect to joystick reversal rates which was consistent with free driving i.e. more lateral turns with the coupled joystick (158.6) compared to the uncoupled (158.6 vs. 116.5, F(1,15) = 55.17, p < 0.05 (1.0)). No interactions between the experimental conditions were found.
Driving behaviour data were also analysed when the driver group was split according to their ASIA scores. Two significant differences were found between the two groups with respect to mean lateral position and mean TLC\textsubscript{min} right. For the group with low ASIA scores it was found they drove on average 12 cm more to the right with the coupled joystick, 2.33 m compared to 2.21 m for the uncoupled (F(1, 7) = 10.26, p < 0.05, (0.8)). This meant that they drove on average with 55 cm offset to the right and rather close to the right lane marker, on average 36 cm. This was twice the difference found for the total group. The other group with better arm/hand function did not show any significant differences in lateral position between the four joystick designs. In line with this result, it was found that low ASIA score group had a mean TLC\textsubscript{min} left which was significantly higher (F(1, 7) = 6.44, p < 0.05, (0.6)) for the coupled joystick (5.86 s) compared to uncoupled (5.05 s). This difference was not observed for the total group. Otherwise both groups conformed to what was found for the total group, i.e. the differences with respect to lateral joystick reversal rate remained. Finally, the analysis of driving behaviour during car following situations did not reveal any differences between drivers with high and low ASIA motor scores. There were no significant interactions found.

**Driving performance - lane change manoeuvres**

The lane change manoeuvres were carried out six times for each of the four conditions. Two drivers did not do the lane changes as they experienced some feeling of simulator sickness during the training. Thus, the analysis was based on data from fourteen drivers performing 336 lane changes. The overall performance in terms of hit cones was not influenced by the joystick design, i.e. even distribution of hits. One cone was hit per three manoeuvres on average. The joystick design did not influence the speed control differently in terms of mean speed. However, speed control degraded tentatively from the first to the second lane change as the standard deviation in speed increased from the first to the second lane change (0.58 vs. 0.68 km/h). The analysis joystick reversal rates revealed that the drivers made significantly more lateral joystick turns with passive feedback compared to active (21.1 vs. 18.9, F(1, 13) = 12.01, p < 0.05 (0.9)). The correlation between lateral and longitudinal joystick motions was much higher for the coupled joystick design compared to (0.53 vs. 0.17, F(1, 13) = 182.09, p < 0.05, (1.0)). There were no significant interactions.

Lateral position data from the manoeuvre test was also analysed in order to find out which of the cones the drivers hit when they did not succeed with the lane change (Figure 3). The cone that was most frequently hit (50 %) was number eight. This cone was placed to the right in the first pair of the second group of cones. This cone determined the entrance into the second row of cones. The second most frequently hit cone was number thirteen (17 %) followed by number 12 (11%). These two cones determined the second lane change. The distribution of hits across the drivers was quite unevenly distributed. Three drivers were responsible for 56 percent of the hits. If these drivers were excluded then the distribution of hits was different form what was found for the total group. The remaining 44 hits were distributed as 36, 25, 24, and 16 percent for CA, CP, UA and UP respectively.
The lane change manoeuvres were also analysed with respect to differences in the participants’ arm/hand motor function. Two significant differences between the two groups were found. The group with lower ASIA scores moved the joystick more longitudinally (i.e. speed control) compared to those with higher scores, standard deviation of longitudinal joystick motions was (2.02 vs. 1.19, F(1,12) = 17.01, p < 0.05, (.97)). In general it seemed like the group with low ASIA scores moved the joystick more than the other group of drivers, even though this difference was only tentative (10% significance).

**Physical and mental workload – physiological measures**

Physiological measures were included in order to measure both physical and mental workload. The physiological data were not complete. First of all, there were two participants that did not perform the lane changes as mentioned earlier. Furthermore, there were two more drivers for which there were technical problems with the recording. The analysis with the total group of drivers included 11 – 13 out of 16 drivers. When the drivers were split in two groups there were between four and seven drivers included in the analysis. One significant main effect was found. The relative load on the trapezius muscle was lower for the uncoupled joystick compared to the coupled when performing the lane change manoeuvres (15.4 vs. 23.7, F(1,11) = 8.71, p < 0.05, (0.8)) for total group. There were no significant interactions.

Spinal cord injuries affect muscular function. Therefore, great individual differences were expected for EMG data due to the magnitude of the participants’ disability. Thus, physiological data were analysed with ASIA score based grouping as between group factor. However, it turned out that there were no significant differences between those with low and high ASIA motor scores and there were no significant interactions. However, the relative muscle load seemed to be consistently higher on the drivers with lower ASIA scores. When data from the two groups were analysed separately it was found that for drivers with ASIA scores over 15 there was a main effect of uncoupled control on the relative load on the trapezius muscle during lane changes (8.2 vs. 18.7, F(1,5) = 8.58, p < 0.05, (.7)).

Finally, an analysis was done using data only from the second drive for all conditions. The assumption was that the drivers were most skilled during the second drive and workload could be lower. The difference in load on the trapezius muscle during lane change found in the overall analysis remained, uncoupled less loading than coupled (15.7 vs. 24.8, F(1,11)=10.3, p < 0.05, (.8)). As before, the relative load was less on the trapezius muscle for drivers with...
high ASIA scores when they drove with the uncoupled joystick (8.4 vs. 18.8, F(1,5) = 10.57, p < 0.05, (.7)). In additions, it was found that drivers with low ASIA scores had a lower heart rate (F(1,4) = 7.84, p < 0.05, (.6)) when driving with the uncoupled joystick during lane changes. The same group had a higher HRV (less mental load) during car following with active feedback (F(1,6) = 7.30, p < 0.05 (.6)). There were no other significant differences or interactions with respect to the tested joystick designs.

**Drivers’ opinion**

Three different questionnaires were used to capture the drivers’ opinion at different stages of the experiment. The first questionnaire included eight questions which were used to capture the drivers’ opinion about performance, effort and experienced control. These questions were asked both for the rural road driving and the manoeuvre test right after the participants had concluded the drive with each joystick design. Semantic differential scales with seven steps were used to give answers were “1” indicated very bad/little/easy and “7” very good/much/difficult respectively.

The following was found for the rural road driving. In general the drivers thought they performed closer to “good” than “bad” for all four conditions (5.1 – 5.4). In general they experienced that the effort (mental and physical) they spent was closer to “very little” than “very much” (2.5 – 2.9). Physical effort scores were lower than mental for all conditions (1.9 – 2.3 vs. 3.1 – 3.3). The questions about control were formulated as “How easy or difficult did you think that it was to control…..?” In general they thought it was rather easy to control steering (2.8 – 3.2), accelerating 2.3 – 3.3) and braking (2.8 – 3.6). Simultaneous control was also considered easy (2.9 – 3.3). The differences between the four joystick systems were not significant and there were no interactions. Furthermore, there were no differences between the two groups of drivers (low and high ASIA scores).

The results for the manoeuvre test were rather similar to what was found for driving on the road. However, the drivers thought they did not perform the lane change manoeuvres as good as driving on the road but still closer to “very good” than “very bad” for all four conditions (4.4 – 4.6). In general they experienced that the effort (mental and physical) they spent was rather low (2.9 - 3.1). Physical effort scores were lower than mental in general (2.0 – 2.3 vs. 3.0 – 3.5). Furthermore, they thought it was rather easy to control steering and accelerator simultaneously (3.2 – 3.8). Braking was not used in the manoeuvre test. There were no significant differences or interactions between the four joystick designs for the total group. However, drivers with low ASIA scores thought accelerator control was more difficult (3.9) compared to those with high ASIA scores (2.8) (F(1,11) = 5.27, p < 0.05, (.55)) and that it was more difficult to simultaneously control steering, accelerator and brake (4.0 vs. 3.1) (F(1,11) = 5.37, p < 0.05, (.56)). The two previous questions were also analysed separately for each group. It was found that drivers with high ASIA scores thought is was easier to simultaneously control steering and accelerator with active feedback (2.8) compared to passive feedback (3.4) (F(1,5) = 10.00, p < 0.05, (.72)). No other significant differences or interactions were found.

The second questionnaire was answered two times once per each occasion i.e. after driving with the coupled and uncoupled joystick. The questionnaire consisted of eight questions. Seating comfort and stability in the simulator was compared to the situation in their own cars. Answers were given on a 7-graded scale where “1” meant much less comfortable/stable and “7” much more comfortable/stable. Seating comfort was considered a bit less comfortable compared to their own cars. The average ratings were 3.4 and 3.7 (coupled/uncoupled).
However, seating stability was experienced as approximately the same as in their own cars 3.8/3.9 (coupled/uncoupled). The participants experienced the coupled joystick as neither comfortable nor uncomfortable while the uncoupled joystick was considered a bit more comfortable. There were no significant differences or interactions between the coupled and the uncoupled condition. The answers were also analysed with respect to ASIA scores but also in this case there were no significant differences.

The drivers were asked about their preferences with respect to active and passive feedback after each driving occasion. The distribution of preferences with respect to passive/active indicated no clear preference for the total group. However, when the drivers’ preferences were divided with respect to differences in arm/hand motor function it turned out that there was a clear difference between the two groups for the uncoupled but not the coupled joystick (Table 3). Those with high ASIA scores had a clear preference for active feedback for the uncoupled joystick while the drivers with low ASIA scores favoured the passive.

Table 3 Number of drivers divided with respect to ASIA scores who preferred active respectively passive feedback in coupled and uncoupled joystick design for driving control (question 4). Only those drivers with a clear preference were included.

<table>
<thead>
<tr>
<th>ASIA score ≤ 15</th>
<th>Active feedback</th>
<th>Passive feedback</th>
<th>ASIA score &gt; 15</th>
<th>Active feedback</th>
<th>Passive feedback</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uncoupled</td>
<td>0</td>
<td>5</td>
<td>5</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Coupled</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>3</td>
<td></td>
</tr>
</tbody>
</table>

The results from the third and final questionnaire revealed that one driver thought the double lane change manoeuvre was difficult (6 on a 7-graded scale, 1=very easy/7=very difficult). However, most drivers thought the manoeuvre was rather simple, 2.9, for the total group. When asked about their preferences with respect to coupled/uncoupled joystick it was found that 8 out of 15 preferred the uncoupled joystick. One driver thought they were equal. There was no difference in preference with respect to the two driver groups.

**Effects of learning**

The driving task was repeated twice for each joystick design in order to study possible learning effects and differences between the joysticks. A three-way ANOVA was used to analyse driving behaviour and performance data in order to discover differences in learning between the four joystick designs. The three factors included in the analysis were coupled/uncoupled, active/passive feedback, first/second drive.

There were some differences in driving behaviour between the first and second drive. The mean speed was significantly lower during the first drive (92.4 km/h) compared to the second (94.1 km/h) \((F(1,15) = 10.50, p < 0.05, (.86))\). The SDLP decreased between the first and second drive \((0.23 \text{ vs. } 0.22 \text{ m}) \((F(1,15) = 7.83, p < 0.05, (.74))\). Finally, mean \(\text{TLC}_{\text{min}}\) left decreased from 5.51 to 5.17 s during the second drive \((F(1,15) = 13.32, p < 0.05, (.93))\). The standard deviation of joystick lateral position was significantly higher \((F(1,15) = 15.64, p < 0.05, (.96))\) during the second drive \((1.04 \text{ vs. } 1.13 \text{ degrees})\). There were no significant interactions.
There were no effects of learning revealed for the car following situations. However, driving behaviour during the second car following situation per each sequence (2 per condition) and the very last following situation per condition were also analysed in order to find out if the drivers changed their behaviour with increased experience. The first analysis did not show any deviating results from what was found for the total. The second analysis, only the very last car following situation per condition, disclosed two significant differences. The drivers varied the speed more with the uncoupled joystick design, 5.29 km/h, compared to the coupled, 4.83 km/h (F(1,15) = 4.57, p < 0.05 (.50)). Furthermore, they drove 5 cm more to the right with passive joystick control (F(1,15) = 7.02, p < .05 (.70)). There were no significant interactions. A three-way ANOVA of the lane change manoeuvres did not reveal any significant effects of learning.
Discussion and conclusions

Driving behaviour - rural road

Mean speed was in general a bit over signed speed limit. One possible interpretation of this result could be that the drivers felt in control and safe. Furthermore, according to the drivers’ opinion they felt that speed and steering control was fairly easy when driving on the road. Support for this interpretation can also be found when comparing mean and standard deviation of speed (93 respectively 4.5 km/h) to what was found in a driving simulator experiment with the same category of drivers and a similar driving task (96 respectively 4.7 km/h) (Peters, 2001b). The drivers in the cited experiment drove with an ordinary steering wheel and the same type of mechanical hand control they had in their own cars. Even with respect to SDLP were the results from the two experiments comparable (approx. 0.2 m).

Driving more to the right could be a sign of a more cautious driving. The wide hard shoulder and oncoming traffic could have encouraged the participants to drive more to right in order to maintain equal safety margins on both sides. This driving behaviour can be understood in the terms of subjective field of safe travel (Gibson & Crooks, 1938) and safety margins (Ranney, 1994; Summala, 1988; van Winsum, 1996). Oncoming traffic encroached upon the driver’s field of safe travel and it was likely that the driver changed heading direction to compensate and to maintain an as wide as possible field of safe travel or safety margin. The observed differences could be an effect of differences in the joystick design e.g. the drivers felt more in control with the uncoupled design. It seemed like this was especially true for the drivers with lower ASIA scores. The tendency to drive more to the right was also shown in that the driver crossed the right line more frequently than the left and TLCmin left was greater than right. However, there were no differences between the tested joystick designs in terms of TLCmin found even when the analysis was extended to consider alternative lane boundaries.

The analysis also showed that the joystick reversal rates were 30 percent lower for the uncoupled joystick and lowest for the design with uncoupled control and passive feedback. These differences could be understood as uncoupled joystick with passive feedback was the most favourable joystick as driving took place on a fairly straight road. Verwey (1994) meant that super light controls can require continuous corrections which could be very physically tiring. Thus, the uncoupled joystick with passive feedback seemed to have made steering control more relaxed. However, this difference did not show up as a difference in physical load as measured by EMG. Active feedback did, however, not contribute to improve the drivers’ control and could even have been experienced as disturbing for those with a low motor function in their right arm and hand. Specifically, considering that these drivers were less in favour of the active feedback for the uncoupled joystick.

The results from the analysis of lateral control during the car following deviated somewhat from the results found for free driving. The difference in mean lateral position that was found for free driving was not found for the car following situations. It also seemed like the drivers in general drove straighter when following lead cars e.g. the number line crossings were lower and min TLCmin values were generally higher compared to free driving. Car following can be a situation requiring more control in order to maintain sufficient safety margins. Furthermore, the difference between active and passive feedback with respect to lateral joystick reversal rates found for free driving was not found for car following. However, there was a significant
difference in left min $TLC_{\text{min}}$ with respect to feedback. Active feedback resulted in lower $TLC_{\text{min}}$ values to the left. Furthermore, it turned out that they drove more to the left with the active feedback compared to the passive when only the last following situation for each condition was considered. These two results could be interpreted as the drivers felt they were in better control with the active feedback and needed less safety margin to oncoming vehicles. Finally, the significant difference between coupled and uncoupled design in terms of joystick lateral turns was also found for the car following situations, which strengthen the support for the hypotheses that uncoupled joystick had advantages over the coupled as discussed for free driving. However, the car following was included to specifically study the drivers’ longitudinal control. In a simulator experiment with the same category of drivers who drove with and without an adaptive cruise controller (ACC) it was found that mean TH was approx 2.5 s respectively 3.3 s with and without ACC (Peters, 2001a). Thus, the min TH found in the current experiment, approx 2.5 s, indicated a very careful driving behaviour with more than sufficient longitudinal safety margins. The average distance to the lead vehicle was over 45 m and min TTC values over 25 seconds. Speed was varied more with the active feedback, which could be a sign of more active driving when only the last following situations were considered. However, this interpretation should be considered as very tentative as it was hard to find other support for this assumption. It seemed like the car following demanded more control but no differences were found between the joystick designs.

In conclusion, there seemed to be evidence that the uncoupled joystick was superior to the coupled in terms of better control and less load on the driver during free driving. However, concerning feedback were the results not so clear. Active feedback seemed to be less favourable than passive for drivers with lower ASIA scores but there were some positive effects of active feedback during car following. Finally, there was no support for any of the hypotheses in terms of longitudinal safety margins.

**Driving performance - lane change manoeuvres**

The double lane change manoeuvres were included in order to force the drivers to test the four joysticks under more demanding conditions. Even if almost one hundred cones were hit during the manoeuvre test it seems like the lane change manoeuvre was not too difficult. The drivers rated their performance closer to good than bad. All except one driver thought the manoeuvre was rather simple. Thus, it seems like the manoeuvre was rather well designed. The analysis disclosed some significant differences between the tested joystick designs. Active feedback resulted in a lower joystick reversal rate compared to passive and the drivers could steer with less influence on speed with the uncoupled design. This supports the assumption that the active feedback and uncoupled control made it easier for the driver to perform the manoeuvre test. The positive effect from active feedback and uncoupling persisted even when only the last manoeuvres were included.

The significant differences in joystick control discussed above did not show up as differences in number of cones hit. Performance in terms of struck cones was a rather rough measure. However, the distribution of hits gave an indication of where the difficulties were. It was found that 50 percents of the collisions occurred when finishing the first lane change and entering the second line of cones. The second lane change seemed to have been performed a bit better than the first in terms of hit cones. However, both cone twelve (start of lane change) and thirteen (end of lane change) were hit in the second lane change. The change in speed was greater during the second lane change. This could have been caused by a decrease in speed in order to improve the steering control. The lane change data were also analysed with respect to
differences in ASIA motor scores. The results indicated that the drivers with better arm/hand function had better speed control during the lane change or at least these drivers had to work less in order to be in control. Furthermore, the drivers with lower ASIA scores moved the joystick more in the longitudinal direction and had a higher variation in speed. These results conformed well to the drivers own opinion, drivers with low ASIA scores thought it was more difficult to control speed and simultaneously control steering and speed.

In conclusion, the uncoupled design seemed to provide somewhat better control for most drivers in the lane change. Active feedback had a positive effect on joystick reversal rates but it seemed like it was only drivers with better arm and hand motor function that could benefit from the active feedback.

**Physical and mental workload – physiological measures**

The relative load on the trapezius muscle (shoulder) was higher for the coupled joystick design during the lane change manoeuvres. When the data were analysed with respect to the two groups with different ASIA scores it turned out that the difference in trapezius muscle load between coupled and uncoupled design during lane changes emerged from the drivers with higher ASIA scores. These drivers experienced significantly and consistently lower load on the trapezius muscle during lane changes when using the uncoupled joystick. This could be interpreted as these drives could benefit from the uncoupled joystick design but not the drivers with less motor function. In conclusion, there was some support for the hypothesis that uncoupled design was less physically loading specifically for drivers with better arm and hand motor function. However, there was no support for the assumption that active feedback should have contributed to a lower mental and physical load on the drivers.

**Drivers’ opinion**

The drivers thought they performed rather well, somewhat better for rural road driving than for the lane change manoeuvres. The workload in terms of effort was not considered to be very high and physical workload was estimated as being lower than mental. Steering and accelerator control was experienced as a bit more difficult for the lane change compared to rural road driving. This seems to be a rather reasonable result. Active feedback was experienced as positive with respect to simultaneous steering and accelerator control especially for those with better motor function. Thus, it seemed like drivers with better arm/hand function were able to benefit from active feedback but not those with less function which also conforms to other results. The answers to the second and third questionnaires showed that seating comfort and stability was acceptable and should not have affected the experimental results. There were no differences between the two groups of drivers with respect to comfort and stability. The results showed also that there was no definite preference for either coupled/uncoupled or active/passive for the total group. However, the drivers with better arm and hand motor function had a clear preference for active feedback in combination with the uncoupled joystick. In conclusion, there was no clear preference concerning coupled or uncoupled design and active feedback was not adjusted to drivers with less motor function.

**Effects of learning**

The results were also analysed in order to find out if there were any differences with respect to learning between the four joystick designs. It was hypothesised that both uncoupled design and active feedback would contribute to make it easier to learn to use the joystick. However, there was no support for this assumption in the results. There was some effect on driving behaviour in rural road due to the repetition of the driving task but not for the lane
change manoeuvre. The drivers seemed to be a bit more active during the second drive in terms of steering control. This resulted in a significantly decreased SDLP and a decreased safety margin to the left. In total this could be interpreted as the drivers were more skilled in their steering control during the second drive. Thus, there was a difference between first and second drive which was expected. In conclusion, there were no significant differences revealed between the four joystick designs in terms of how easy it was to learn to drive.

**Methodological considerations**

The analysis clearly revealed that even if the group of drivers were selected to be as homogenous as possible in terms of functional ability, they were not. This is a fundamental research problem when addressing drivers with disabilities. These drivers can be very different and this is the reason why it is often claimed that vehicle adaptations has to be made individually (Oliver, Paton, & Perry, 1997; Strano, 1997). The need for individual adaptation becomes more pronounced with increasing disability. Maybe a more homogeneous group of driver would have given a different result. The drivers with better motor function in their right arm were more in favour of active feedback compared to those with less function. This could have been caused by the fact that the feedback forces were not individually adjusted. Active feedback increased system inertia and could have made the control more loading to the drivers with lower motor function.

Measures of time-based safety margins, e.g. TTC, TH, and TLC, did not reveal any consistent differences between the joystick designs. It is possible that a more detailed analysis of these measures could have disclosed some more information concerning the tested features. However, the analysis of how the drivers actually handled the joystick lever, e.g. joystick reversal rates, variation in motions and correlations between lateral and longitudinal motions during specified control tasks, seemed to be useful to discover important differences between the designs. Even if these measures can be useful for an adaptation evaluation they have to be combined with driver behaviour, physiological, and subjective measures. The evaluations should also consider the specific driving task, e.g. braking and steering, steering at constant speed.

Time lags can be very difficult to handle for a driver (Jagacinski & Flach, 2003, chapter 9; Wickens, 1992). Time lags refer to both delayed reactions and the dynamic relation between displacement of the joystick lever and the behaviour of the car. Thus, time lags can be divided into order of control (e.g. position, speed or acceleration control) and pure time delays (Jagacinski & Flach, 2003). As long as the time lags are relatively short there is usually no problem for the driver to control the car. The time lags in the steering systems of standard cars do not cause the driver any problems on the contrary they rather contribute to make steering more stable. However, when the time lags long it will be difficult for the driver to predict the behaviour of the car. Despite being inexperienced, the participating drivers performed much better e.g. in terms of hitting cones than what was observed for experienced joystick drivers (Östlund & Peters, 1999). Thus, results support the suggestion that time lags in joystick systems should be made similar those found in conventional controls of standard cars.

The manoeuvre test consisted originally of two tests, the double lane change and a braking manoeuvre in a curve. Similar to what was used in the manoeuvre test conducted by Östlund and Peters (1999). However, braking in a curve turned out to be very complicated to simulate and during some initial tests it was found that there was a high risk that the drivers would experience simulator sickness. Thus, this manoeuvre had to be abandoned. If it had been possible to include the brake manoeuvre it might have revealed some critical differences between the joystick designs. The same manoeuvre was previously found to be revealing in
terms of control interference (Östlund & Peters, 1999). However, the results from this experiment has shown the usefulness of including a manoeuvre test in an adaptation evaluation, even if such a manoeuvre test needs to be further developed in order to disclose erroneous or in sufficient adaptations.

**Conclusions**

The following conclusions in relation to the four hypotheses were drawn in view of the results discussed:

1. **Uncoupled lateral and longitudinal control**
   - had some positive effects on both driving behaviour and performance
   - contributed to a lower physical workload but no effect on mental workload
   - the positive effects were more pronounced for drivers with good motor function
   - there were few differences in terms of safety margins between the designs
   - there was no clear preference expressed by the drivers with respect to uncoupled or coupled design

2. **Active feedback**
   - did not contribute to improved control for rural road driving
   - provided better control in the lane change manoeuvres for drivers with good motor function in right arm and hand
   - was less favourable or even disturbing compared to passive for drivers with less motor function in right arm and hand
   - did not influence neither physical nor mental workload
   - in combination with the uncoupled joystick was preferred by drivers with good motor function

3. **The combination of uncoupled control and active feedback**
   - seemed to be favourable for the drivers with good arm function
   - was not superior compared to the other designs for the drivers with less motor function which could be a result of lacking individual adaptation of the joystick

4. **Learning to drive with the joystick**
   - was not easier when the lateral and longitudinal controls were uncoupled and active feedback provided compared to the other designs
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