Joystick-controlled cars for drivers with severe disabilities

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This report was commissioned by the Vehicle Standards Division of the Swedish National Road Administration and is included in the project "Joystick-controlled vehicles for drivers with disabilities". The aim of the report is to describe and analyse commercially available joystick systems in Sweden. Furthermore, general considerations to be taken in the design of alternative primary levers (for driving) are emphasised.

A small group of people with severe disabilities regain an essential part of their mobility thanks to joystick-operated cars. People currently requiring joystick-operated cars have disabilities resulting in limited mobility and/or strength in arms and legs.

A joystick includes accelerator, brake pedal and steering wheel in one lever. The analysed joystick systems have a joystick with spring-feedback and do not have the mechanical connection with the steering wheels and brake system. The result is that much information fed back to the driver in a conventional car by means of steering wheel and pedals is lost. Since the joystick is designed as a lever, fastened at one point and with two control directions, lateral and longitudinal controls may interfere. Further shortcomings can be identified for joystick-operated cars but their influence on traffic safety is difficult to decide.

Information and knowledge have been gathered to the knowledge survey through literature studies in the field and contacts with vehicle adapters, driving license instructors and drivers with disabilities.
Foreword

This report was written at the request of Jan Petzäll, from the Vehicle Standards Division of the Swedish National Road Administration (Vägverket). The report is part of the “Joystick-controlled vehicles for drivers with disabilities” project, which also includes a questionnaire survey and a report on a maneuvring test conducted among joystick drivers.

This report is a review of the current knowledge in the area and is based on the results of research into humans as operators of dynamic systems, the know-how of vehicle adapters, the experience of drivers of joystick-controlled vehicles and the know-how of the automobile industry. A literature search has been made in the following databases: Compendex, NTIS, SAE, TRIS, Psycinfo, IRRD, Roadline and Medline. These databases cover the research that has taken place in the areas of practical technology, transport, rehabilitation and medicine.

I am very grateful to Björn Peters, researcher at the VTI and my tutor, who offered me considerable help and provided me with the opportunity to involve myself in this project. I should also like to thank Autoadapt AB and Anpassarna Gunnérius AB, who were very helpful and provided me with many valuable comments. Finally, my thanks are due to Staffan Nordmark (Professor of Vehicle Dynamics at the VTI), who was sponsoring editor at the report seminar.

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Summary
Joystick-operated cars for disabled drivers have been used for 10 years and in Sweden there are about 15 people using such cars. Despite this fact, in Sweden no evaluation of joystick-operated cars has been carried out from the Human Factor perspective or man-machine perspective.

Joystick-operation and Human Factors
With the aid of a joystick, a small group of severely disabled people can accelerate, brake and steer a car with e.g. one hand, and thus regain a considerable proportion of their mobility. Before this project started there was no documented information on these severely disabled drivers’ possibilities of handling their cars in a safe and comfortable way. Guidelines or regulations for vehicle adaptors are not sufficiently detailed when designing such advanced operation systems as joystick systems in the car. The aim of the knowledge survey is to describe the knowledge situation concerning the possibilities of operating a car with a joystick and to analyse the joystick system from the man-machine perspective and note where improvements should and can be made.

Design
A joystick is a lever mounted at one end in a ball-and-socket joint with two degrees of freedom, forward–backward and left–right. The joystick has spring feedback, meaning that the information to the driver in a conventionally equipped car via steering wheel and pedals is lost to a great extent. The joystick system acts on steering, accelerator and brakes with the aid of hydraulic or electronic position feedback servounits.

Risks
By studying the joystick system and other types of levers for acceleration, braking and steering from the Human Factors perspective, it was possible to identify the following potential risks and problems with cars operated by joysticks.

- **Time delay in the control system:** It is possible to manoeuvre the joystick faster than the reaction of the other control system, so in fast manoeuvres a time-delay dependent on amplitude and frequency is introduced
- **Braking difficult to learn:** The brake is angle-operated with no feedback of the braking effect and in most cases the transfer function is non-linear, resulting in a probably more mentally demanding braking task than necessary.
- **Interference between accelerator/brake and steering:** This effect depends on the fact that the joystick is angle-operated for both steering and accelerator/brake and that there is a joint rotation point for these functions. Furthermore, there is no feedback of information on the reaction of the car to operating movements in the lever.
There are currently about fifteen active joystick drivers on Sweden’s roads. Around twenty cars in total are equipped with joystick systems. Access to a joystick-equipped car enables a group of persons with severe disabilities to take care of a large proportion of their own transport requirements. This contributes to increased freedom and a higher quality of life. From being entirely dependent on personal assistants and the transportation service for disabled persons, these people are now able to provide a large proportion of their mobility themselves with their own car.

A joystick operating control combines three primary control functions (steering, accelerating and braking) in a single electronic operating control. There are at present no specific requirements or specially developed procedures or methods of testing for joystick-equipped cars. The Swedish Motor Vehicle Inspection Company (Bilprovningen) imposes the same requirements on these cars as on standard production cars. The aim of this project is to investigate what problems may be associated with this technology and to suggest appropriate measures and improvements.

Vehicle adaptation companies and developers of joystick systems are to some extent aware of the risks and shortcomings inherent in joystick-equipped vehicles. It is clear that joystick systems can be difficult to operate in certain cases and, for this reason, they are frequently regarded as a final adaptation alternative. In spite of this, however, no work has previously been carried out into the evaluation of joystick systems in Sweden. An initial approach to the identification of problem areas is to ask the following questions: (1) How must the joystick be designed in order to optimize the possibilities for controlling a car? (2) How must the driver’s control movements be transmitted via the joystick to the car in order to guarantee its reliable function with a minimum risk of interruption? (3) How must the exchange of information take place between the car and the driver via the joystick in order to facilitate the task of driving and make it as simple, comfortable and safe as possible?

This project is targeted essentially at analyzing (1) and (3), because these problem areas are considered to have been researched to a far smaller extent than (2). In order to give an appreciation of the circumstances, problems and risks that may be associated with joystick control of cars, it is necessary to carry out a detailed investigation of the existing theory and know-how in respect of the ability of humans to drive a car or to control other dynamic systems. This report accordingly includes an account of humans as operators of dynamic systems and the ways in which various system characteristics affect the ability to control the system. This is then applied to the task of driving a car, on the one hand with a conventional primary operating control (steering wheel, accelerator pedal and brake pedal), and on the other hand with alternative primary operating controls, in particular a joystick. To help the reader to appreciate the possibilities and limitations of humans with regard to the manual control of dynamic systems, the report also includes a brief account of the aspects which demand mental resources and those which do not.

The intention is for the theoretical background analysis to identify a number of question marks and potential risks associated with joystick systems. I hope to obtain answers to some of these in a manoeuvring test at the Mantorpanan test track (Östlund, 1999a) and from a questionnaire survey carried out among joystick drivers (Östlund, 1999b). It appears likely that the design of the joystick may cause control movements for steering and accelerating/braking to mutually interfere. Furthermore, the lack of feedback in the joystick may play a part in making the task of driving more difficult and more demanding than necessary.

This project will not result in specific requirements for joystick-controlled vehicles, but it will describe the problem and make suggestions for possible solutions. These problems and solutions will then require further detailed investigation to enable specific requirements or guidelines to be formulated.
People with functional disabilities find it difficult to cope with many everyday situations. It is up to them to adapt to their surroundings to whatever extent is necessary, because their environment and surroundings are often regarded as static. Disabled persons become handicapped if they are unable to achieve this adaptation. A change in attitude is essential in order to escape from this anomaly: a person’s surroundings are not static, but flexible and adaptable. Many environments are clearly well adapted to non-disabled persons, but poorly adapted to those with functional disabilities. By designing the environment and surroundings to suit the needs of both disabled and non-disabled persons, many people, including those without functional disabilities, will find life very much easier.

Joystick-controlled vehicles (in which acceleration, braking and steering to the right and left are controlled via a 4-way joystick) make it possible for a group of disabled persons to drive a car. Until quite recently, this group had absolutely no opportunity to drive a car. Joystick control as we know it today has been in existence since the early 90s, although a functional and highly advanced joystick system had already been developed in 1959 and was installed in a Chevrolet (Bidwell, 1959). This system was not intended for use by disabled persons, however.

The people who are considered for vehicles with joystick control often suffer from muscular diseases which leave them with severely impaired strength and range of motion. In exceptional cases, joystick control is also considered suitable for individuals with high spinal injuries (with very weak function in their arms and hands and an impaired sense of touch) or individuals who lack both arms and legs. These individuals are users of electrical wheelchairs in every case. According to the vehicle adaptation specialists, the characteristics required by these individuals in order to be able to handle a joystick are sufficient fine motor control and mobility in some part of their body (hand, foot or chin, etc.). This is often the case in people with muscular diseases, but rarely the case for those with spinal cord injuries, since the latter have damaged nerve paths which often lead to an impaired sense of touch and muscle control.

2 Who need joystick-controlled cars?
This Chapter describes the possibilities and methods available to people for controlling dynamic systems such as a car. The level of mental resources required by an operator to control a system depends on how information is exchanged between the operator and the system and how the system reacts to an operator's control movements. The need for a high level of resources (high mental workload) is associated with the risk of a poorer result. Understanding is essential in this area in order to appreciate the problems and risks that may occur with alternative primary controls when driving a car, and to identify design solutions for the operating controls so that they conform better to people's opportunities and limitations.

3.1 Open and closed loop control

As the operator of a system, a human receives information (stimuli) into his/her short-term sensory store (memory) via one or more of the five senses, processes the information and draws conclusions based on wishes, surroundings and experience, performs an action and stores any information and consequences in the long-term memory. See Figure 1 for an illustration. It is possible to divide an operator's function into two different control functions: open loop control and closed loop control (Wickens, 1992). The former involves executing a movement pattern from start to finish without allowing it to be influenced by external stimuli. The action is predetermined in relation to the operator's wishes, surroundings and anticipated consequences, etc. How good the result of such an action is will depend on how well-adapted it is, which in turn will depend on the operator's experience of similar actions, the amount of time available to the operator in which to prepare for the action, and the extent to which the operator is burdened by other tasks. Closed loop control, or tracking as it is often called, is not based on predetermined actions, but is structured as the need arises. The act of balancing a pencil on a fingertip is based typically on closed loop control. The two types of control are rarely encountered in isolation, rather the predicted movement pattern starts according to closed loop control; but due to uncertainty and unforeseen consequences or events, however, the movement pattern is monitored with the help of tracking. A predetermined action can be disturbed by unforeseen factors, the consequences may not be as foreseen, or the operator may be so stressed or inexperienced that the manoeuvre does not proceed as wished. Many factors play a part in tracking being required to give good control results.

![Figure 1](image-url) Model for information handling (Sanders & McCormick, 1992)
Human limitations and possibilities in open loop control
Actions are often reactions to stimuli from the surroundings. The car in front may brake abruptly, for example, causing the following car to brake. The speed with which an operator responds to a stimulus with the right action and the quality of the result are thus essentially dependent on:

• The number of alternative actions. More alternatives extend the reaction time.
• How well rehearsed the action is. Familiarity gives a quicker reaction time and better results.
• How complex the action is. A complex action takes a longer time to initiate and perform.
• How distracted or busy the operator is.
• How well-prepared the operator is for the situation concerned (Wickens, 1992).

Human limitations and possibilities in closed loop control
A human’s reaction time is defined here as the elapsed time between the change in status of the controlled system being brought to the attention of the operator via a display (visual, tactile and auditory display, or direct observation of the system) and an action being commenced in order to correct the change. The reaction time depends to a considerable extent on how prepared the operator is for the change in condition. If a given change in status is anticipated, the reaction time is 150-300 ms (McRuer & Jex, 1967; Pew, 1974) whereas, if the operator is unprepared, the reaction time is 400-500 ms, i.e. less than half a second. If an operator attempts to control a system that is on the borderline of changing more rapidly than the operator is able to keep up with, there is a considerable risk of over-corrections taking place and the control becoming unstable (Jex & McDonnell, 1996).

Effect of system dynamics on tracking performance
Any amplification between a control movement (applied via an operating control, for example) and the reaction of the system will influence the tracking performance. High amplification gives large reactions for small control movements, which, according to Fitt’s law (Sanders & McCormick, 1992), reduces the work necessary to operate the control to a certain extent, but reduces the accuracy at the same time. Low amplification, on the other hand, gives high work input but high accuracy. Optimal amplification is a compromise between the movement distance and the accuracy (Jex & McDonnel, 1966; Wickens, 1992).

Predictability is an important characteristic of a system. If it is possible to predict the reactions of a system to actions, then good opportunities exist to control it in a satisfactory fashion. Humans find it difficult to predict reactions if time delays are present in the system, because this means that the operator must predict the future consequences of events and make correction for any future disruptions before the system has reacted (Wickens & Fracker, 1989; Zarrugh & Miller, 1982). In stressful situations, such as when several tasks are performed simultaneously, the ability to predict essentially rapid sequences is very poor. The system may exhibit poor stability characteristics, which make it difficult to control. One important factor for predictability is the order of the system. A system of order zero gives a constant output signal for a constant input signal. For example, a specific steering wheel deflection gives a specific deflection of the front wheels, which is thus equivalent to a system of order zero. A system of order one gives a constant change in the output signal for a constant input signal, and so on. Figure 2 shows how the output signal from three systems of different orders is given a constant level (broken line) via control move-

Figure 2   Relationship between system order and step response. Input signal (solid line) and output signal (broken line) for systems of (1) order zero (lines coincide), (b) order one and (c) order two.
ments (solid line). Assume that the input signal and the output signal are one position or deviation away from a neutral position.

In Sub-figure (a) (order zero), the output signal follows the input signal (the constant amplification between the signals is given the value 1). In Sub-figure (b), a constant input signal gives a constant increase in the output signal – a constant speed. In order for the output signal to remain at a set level, the input signal must be brought to the neutral position, where input signal = 0. In Sub-figure (c), the input signal must change its mathematical sign after having given the output signal a constant acceleration value, so that the speed of the output signal is reduced to 0. Once this has been achieved, the input signal must be set to 0. It is obvious that the latter case calls for the greatest moment, which makes it the most mentally demanding. In a mathematical sense, a system of order \( n \) will integrate the input signal \( n \) number of times.

An operator has no problems in handling a system of order zero, and normally no problems in handling a system of order one, although as soon as the order increases to two or higher, the control performance falls significantly (Sanders & McCormick, 1992; Wickens & Fracker, 1989). People find it difficult to experience changes in speed and acceleration, which may offer one explanation for the limitation to systems of a lower order. As soon as the system order increases above zero, however, a time delay occurs between handling and system reaction.

The operating control used to control a system may be either force-controlled or position-controlled (angle-controlled). In the former case it is the force applied to the operating control that constitutes the input signal to the system, and in the latter case it is the position or angle of the operating control. Systems of higher orders with the capacity for rapid change can be controlled to good advantage with a rigid, force-controlled operating control, and system of order zero can be controlled with a position-controlled operating control (Kember & Staddon, 1989).

### 3.2 Compatibility and feedback

Compatibility means agreement, in this case the agreement between how the system is perceived by the operator and how it conforms to the operator’s mental model of the system. It includes the positioning of the operating controls, whether they are force-controlled or position-controlled, the direction in which they are moved, and how information about the system is communicated to the operator, etc. Good compatibility means that the operator can obtain a more correct impression of how the system functions and is thus in a position to predict and interpret its reactions in a correct fashion. This improves the control result and the operator’s reaction time (Wickens, 1992; Wickens & Fracker, 1989). One important component that is rarely used for the control of dynamic systems is tactile feedback in the operating control used by the operator to control the system. This direct contact can provide valuable information, and it is present in all systems that are directly influenced by the operator. For example, a driver is able to sense the road surface through the steering wheel, which enables him to determine to a certain extent how slippery it is and how fast he is driving. In the absence of natural feedback, such as that provided via the steering wheel, artificial (passive or active) feedback can be created to assist the operator in his control task.

**Passive feedback** is feedback that is based on a model of the system, but without taking into account how the system changes (Merhav & Ya’cov, 1976). Because such a model does not communicate the disturbances to which the system is subjected to the operator, it is not possible for correction to be made for these by the operator sensing the disturbances. This is a disadvantage in view of the fact that feedback offers an ideal means of correcting for disturbances. The operator senses via the steering wheel when the front wheels are caused to turn unintentionally for any reason, or if they almost lose their grip, and a correction is made more often than not subconsciously. Passive feedback is very often achieved by means of springs, viscous damping and frictional resistance.

**Active feedback** reflects the actual performance of the system, and disturbances can also be communicated to the operator via the operating control (Merhav & Ya’cov, 1976). Hosman & Bernard (1990) carried out a test in which they compared the control performances during tracking with a disturbance source which changed the status of the system. This test was performed for those cases in which the operating control communicated either passive or active feedback, in which the active feedback was communicated via servomotors. They concluded that there was a significant difference in the results in favour of active feedback. SAAB (Brännby, Palmgren, Isaksson, Petterson & Franzén, 1991; Tunberg, 1991) and Daimler-Benz (Eckstein, 1997) have also demonstrated, in the course of the development of alternative steering controls (not specifically intended for disabled drivers), that active feedback improves the control performance. Active feedback is very often achieved with servomotors.

In spite of the fact that poor compatibility prevails, it is entirely possible for an operator to learn to handle this situation. Charles J. Worringham (1998) maintains that training can minimize the effect of poor compatibility, *although it cannot eliminate it entirely.*
4 Driving a car

This Chapter discusses models of interest to driving behaviour. The intention is to create a structure for understanding what is involved in driving a car. The Chapter analyses and discusses handling the steering wheel, accelerator and brakes and the ways in which these differ from one another. This is necessary in order to be able to analyse alternative primary operating controls. The clutch and gear lever are omitted entirely because all cars equipped with a joystick have automatic transmission.

4.1 A model on three levels

John A. Michon (1985) has developed a descriptive model for driving performance on three levels in accordance with Figure 3. At the highest level (Strategic level), the route is planned and requirements are set in respect of the speed, for example. These requirements, together with the surrounding traffic environment, are used as input signals to the next level (tactical level), which is concerned with the surrounding traffic environment and interactions with other road-users. Failure to meet the requirements is noted at the strategic level, and new plans must then be drawn up. All intentional actuations of the operating controls, such as following the traffic rhythm and avoiding collisions, belong to the tactical level. Also anticipated at this level are the results from the lowest level (operational level), which is concerned with vehicle control purely in terms of motor responses, i.e. steering, accelerating, braking, operating the turn indicators and sounding the horn, etc. This operational level takes account of the surrounding environment and the requirements imposed by the tactical level.

The operational level is of the greatest interest here, since joystick control of vehicles does not extend beyond changing the operative control of the vehicle. This is not really true, because a joystick changes the manoeuvring possibilities and the environment of the driver’s position. These aspects are discussed later, however, in conjunction with the effect of the joystick on the task of driving and active safety.

4.2 A model for lateral control

A common model for describing how car drivers handle the lateral position of a vehicle on the road (sideways) is based on the theory of open and closed loop control (Donges, 1978; Godthelp, Milgram & Blaauw, 1984; Winsum & Godthelp, 1996) and relates most readily to the tactical and operational level in Michon’s model. According to open loop control, the driver continuously develops movement patterns in respect of how to operate the steering wheel and the pedals in order to cause the vehicle to follow a planned course in a safe and comfortable fashion. This predetermined course is then followed through interaction between open and closed loop control.

4.3 Information flow and feedback

Many theories have been advanced, although none of the theories studied in the course of this project have been able to describe in a satisfactory fashion what information from the traffic environment and the driver’s own vehicle plays a part in performing the task of driving. Few experiments appear to have been made to investigate the

![Figure 3](Hierarchical structure of the driving task (Michon, 1985), divided into three levels which integrate with one another through anticipation, requirements and actual sequence of events (upward arrows).)
information the operating controls feed back to the driver, possibly because such experiments are difficult to design and interpret.

The driver’s vision obviously has a part to play in providing an idea of the speed of the vehicle, both by relating the movement of the vehicle to its immediate and distant surroundings, and by reading the speedometer. Since the noise level and the pitch of the engine note increase in relation to the speed of the vehicle, it is very likely that the driver’s hearing also contributes to the perception of speed. The hearing can be particularly important for determining variations in speed, given that human hearing has an excellent ability to distinguish between variations in pitch. Humans experience difficulty in perceiving variations in speed visually (Winsum & Godthelp, 1996), which further increases the importance of sound. Tactile feedback is provided in the vehicle via vibrations, which change with the speed, which means that they can be significant. However, the most obvious tactile feedback is provided by changes in speed (longitudinal accelerations) being perceived by the body’s sensory and balance system. Very little research has been done into these factors, however.

The lateral acceleration of a vehicle depends on the speed of the vehicle in a square, which is why the lateral force at a given steering wheel deflection can convey a feeling of how fast one is driving (Herrin & Neuhardt, 1974; Kanellaidis, Golas & Efstathiades, 1990; Macura, 1984; McLean, 1981).

It is obvious that the driver uses his vision to perceive the lateral position of the vehicle and any changes in it. However, the senses of touch and balance and a perception of the state of the body are also important factors for providing information about changes in the lateral position of the car (Alm, 1995). The senses of touch and balance are rarely discussed in conjunction with the task of driving a car, although bearing in mind compatibility and the overloading of the other senses, touch can play a decisive role in control tasks which call for rapid decisions and actions (Merhav & Ya’cov, 1976; Wickens, 1992).

4.4 Handling of primary operating controls

With reference to the above paragraph, how does a car driver operate the steering wheel, accelerator and brakes? What characteristics of the steering system, acceleration system and braking system does a car driver use in order to handle the car’s dynamics and characteristics in an optimal fashion in a complex traffic environment? Important questions in this respect are how the driver controls the vehicle via the operating controls, what information the operating controls feed back to the driver, and how this information is fed back. This analysis is of great importance to the evaluation and analysis of alternative primary operating controls, since it may be important not to eliminate, distort or disturb aspects of the communication between the vehicle and the driver.

Operating the steering wheel

A car driver’s intention in steering is to follow a predetermined course with reference to requirements from the traffic environment and wishes for comfort (Michon’s strategic level). Steering seeks to control a position (Donges, 1978). A given deflection of the steering wheel causes the front wheels of the car to turn through a given angle in accordance with a system of order zero. With the vehicle travelling at a constant speed, this generates lateral acceleration equivalent to a system of order two. Since the driver perceives lateral acceleration and visual change in the position of the vehicle on the road at the same time as the vehicle requires to be controlled to a given lateral position, it is reasonable to assume that the driver perceives a system of order two.

As already mentioned above, force control is often the best alternative for controlling systems of higher orders, which is why the position-controlled steering wheel would not be the optimal solution. If a steering operating control were to be force controlled, a given force would correspond to a given steering deflection. However, since it is not possible to cause the front wheels to turn at the same rate at which it is possible to change the force on an operating control, rapid manoeuvres would often include periods during which the driver is unaware of the position of the front wheels; the result is time delays. As far as the steering wheel is concerned, the angular deflection of the front wheels and the forces that affect the front wheels are fed back to the steering wheel, which facilitates the task of steering. The steering wheel may have a large working range as is turned, and by moving the hands on the steering wheel the driver can always optimize his mobility and his strength to suit the curvature of the road. The steering wheel has a working range of less than four revolutions, whereas the range of deflection of the front wheels is of the order of a quarter of a revolution. This ratio is necessary in order to be able to handle the car at high speeds. This discussion is developed further in “Alternative primary operating controls”, where it emerges that a sufficiently large working range is critical for alternative steering controls. The steering wheel with which we are familiar today, with its mechanical coupling to the front wheels, appears to be the best alternative from the point of view of handling.
Operating the brake pedal
When the driver presses the brake pedal with a certain force, a corresponding frictional force is generated between the brake linings and the brake discs/drums, which in turn causes the vehicle to brake or decelerate. Since a car has a built-in inertia, force-control of the brakes is probably the best alternative from the point of view of compatibility, given that the laws of physics state that the application of a constant force to a mass gives accelerated motion in the direction of the force. Compared with the steering wheel, the spatial operating area for the brake pedal is small. The force-related operating area for the brake is large, on the other hand. The need for positional control for the steering wheel has no equivalent for the brake pedal, since the braking system has no inertia that requires to be counteracted.

Operating the accelerator pedal
The accelerator pedal is angle-controlled, and the relationship between the accelerator pedal and the speed of the car on the road can be described with a low-pass filtered system of the order zero when the aim is to drive at a specified constant speed which is achieved with a constant accelerator setting. The system order and the manner of handling the accelerator correspond closely in this case. The dynamics of the car’s acceleration and speed are restricted to slow changes which do not demand precision. The accelerator setting changes rarely compared with the steering, and the accelerator operating control is kept constant for long periods on main roads in particular. Furthermore, the accelerator is rarely used in emergency situations. This means that the requirements for the accelerator operating control to be optimal from the point of view of a human-machine interaction need not be as strict as the requirements for the braking and steering operating controls.

Discussion of interference between the tasks of steering, accelerating and braking
How does a car driver manage to combine the task of steering with that of accelerating and braking? If all the relevant movement patterns are well-rehearsed for all conceivable situations and combinations, experience shows that this will function well without major problems in normal traffic situations. Less well-rehearsed actions are put to the test in emergency situations. If the movement patterns concerned are not sufficiently well-rehearsed, it will not be possible to adapt them sufficiently well to enable them to be performed correctly. It is difficult to decide whether the design, mode of operation and positioning of conventional operating controls could be more favourable. Because the operating controls are physically separate from one another, it is not possible for interference to occur as the result of an unintentional movement of the operating controls. The task of steering is also so separate from the operation of the accelerator and brakes that there is also no risk of using the wrong operating control, for example to perform a braking manoeuvre. Movement compatibility in respect of how the steering wheel is operated and force compatibility in respect of how the brakes are operated are in line with the results and recommendations produced by research into the manual control of dynamic systems. The tasks of steering, accelerating and braking are separate as far as handling the operating controls and feedback are concerned. It is difficult to find any aspect of the steering wheel or the accelerator pedal or brake pedal that could result in an incorrect manoeuvre being performed as a consequence of interaction between the operating controls.
This Chapter discusses, analyzes and compares typical alternative primary operating controls with the conventional primary operating controls covered in earlier Chapters. The intention is to make the reader aware of what alternatives to the joystick are available and how they function. The most important aim, however, is to draw attention in a structured fashion to the problems that may arise with different types of alternative operating controls; these problems lie with the joystick in many cases. The unique feature of the joystick is that it combines three control tasks (accelerating, braking and steering) in a single operating control. A more conventional way of combining operating controls is simply to adapt a car with separate operating controls for steering and accelerating/braking. Joystick control is not discussed specifically in this Chapter.

The following important technical features of alternative primary operating controls can be identified:
- Design of the operating control
- Working range of the operating control
- Transfer function of the control system (between the operator’s control movement and the reaction of the system)
- Tactile feedback from the operating control

The control system and the operating control are separated in such a way that the operating control acts as the control system’s interface with the driver. The transfer function of the control system defines how the control object (the object that it is wished to be controlled) responds to the operator’s control movements. The control system is defined as the combination of operating control, control object and mechanical, electronic, hydraulic or pneumatic connection between the operating control and the control object. To take one example, the steering wheel is an operating control, the front wheels are the control object, and the connection between the steering wheel and the front wheels is mechanical. In order to be able to control a system, the operator must have a control objective which the operator attempts to cause the system to achieve.

### 5.1 Control characteristic

Control characteristic is the expression used to denote the transfer function of the control system, the working range of the operating control and the tactile feedback from the operating control. This section discusses important factors which affect the control characteristic of the control system in the area of vehicle control.

**System order**

One important characteristic of control systems is the order of the system or its transfer function, as discussed in the Chapter “Mental resources and manual control of dynamic systems”. To take a familiar example, the system from steering wheel deflection to front wheel deflection is approximately of the order zero, as follows:

\[ u = k \cdot v \]  

where \( k \) is a constant, \( v \) is the steering wheel deflection (angle), and the corresponding angle of the front wheels is \( u \) (see Figure 4 for a definition of angles).

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**Figure 4** Definition of steering wheel deflection and front wheel deflection. The steering wheel deflection is the angular deviation from the “straight ahead” neutral position. The front wheel deflection is the corresponding angular deviation by the front wheels.
If an object needs to be controlled with some type of operating control, e.g. a lever or wheel, the question concerns which characteristic of the control object needs to be controlled: position, speed or acceleration. The system order required by the control system should be selected, if possible, so that it harmonizes as closely as possible with the mental model of the control object, and so that the compatibility is as high as possible. More often than not, a linear relationship (order zero) between the deflection of the operating controls and the reaction of the system is the best alternative, for example constant deceleration is given by a certain force on the brake pedal.

**Time delay**

The conventional steering wheel is mechanically connected to the front wheels, and there is no time delay between the steering movement and the change in the deflection of the front wheels. A time delay of 0.1 to 0.2 seconds does exist, however, between the deflection of the front wheels and the reaction of the vehicle on the road (Zomotor, 1987). The strength of the driver, the inertia of the front wheels and the frictional force present in the whole steering system (primarily between the wheels and the road) all limit the speed with which steering movements, and consequently steering manoeuvres, can be performed. In an electronic or servo-assisted steering system without mechanical connection to the steering mechanism, it is possible to perform steering movements that are too rapid for the steering servo. This means that an amplitude-dependent and frequency-dependent time delay is built into the steering system. In the case of lever control in particular, there may be a risk of performing excessively rapid steering movements under stressful situations, which is where the time delay may reappear in the form of a delayed deflection of the front wheels. Very little research has been done in this area, however.

**Lateral control**

The range of deflection of the front wheels is large in relation to the range used when driving on main roads. A rough correction of the lateral position on a main road does not, as a rule, call for a change of more than about 1 degree in the angle of the front wheels, which corresponds to less than 1% of the entire deflection range of the front wheels. With an ordinary steering wheel, there are no problems in making such corrections, because this corresponds to a change of about 20 degrees in the deflection of the steering wheel. One demand which must be imposed on an alternative operating control is a sufficiently large working range for the operating control to provide opportunities to make a sufficiently large range of adjustments to the position on the road, including at high speeds. This requirement must then be related to the freedom of movement of the driver. There is no problem in the case of drivers who steer with a steering wheel, because the steering wheel rotates. It is not so good in the case of lever steering, however, more about which later.

It is not obvious what kind of transfer function alternative steering systems need to have, although it is clear that problems occur with alternative steering controls when the entire range of deflection of the front wheels needs to be controlled with a steeply reduced working range in relation to the steering wheel. It is thus of interest to compensate for this limitation in some way.

A general expression for the angle of deflection \( u \) of the front wheels with regard to the deflection \( s \) of the steering control can be stated as: \( u = f(s) \), where \( f \) is a continuous function of order zero in the actual control deflections. The number of ways of achieving this function is infinite. The function may be linear, for example, as shown in Equation 1 (Figure 4), which corresponds to the transfer function between the steering wheel and the front wheels. The function may be quadratic: \( u = k \cdot s^2 \cdot \text{sgn}(s) \), which should concentrate a larger proportion of the working range of the operating control into small angles of deflection for the front wheels (from the neutral position, when \( u \) and \( s \) are zero) compared with the linear function.

A complement to the amplification between the deflection of the operating controls and the deflection of the steering wheel is an amplification which depends on the speed of the vehicle: the higher the speed, the lower the amplification. This function means that the largest possible proportion of the working range of the steering control can be used at all speeds (Brännby et al., 1991; Eckstein, 1997). Brännby et al. (1991) use a reduction in the amplification with regard to the speed in accordance with Figure 6. A disadvantage is that, if the car skids at high speed and the driver must resort to a large deflection of the front wheels in order to correct the skid, this may prove difficult because of the steering limitation.

A second alternative for reducing the problem of an excessively small fine adjustment range is for the control system to have built-in low-pass filtering (damping) dependent on the speed, in such a way that the steering becomes softer in proportion to the speed of the car. This type of steering means that the problem of making small deflections of the front wheels with small movements of the lever can be compensated for by performing rapid movements at large amplitude. A lateral correction of the position of the vehicle can be made by performing a larger control movement with the lever for a brief moment. What would happen in this case if the driver
genuinely wanted to perform a really rapid manoeuvre? The low-pass filtering includes a time delay, which can interfere rather than help in situations which call for rapid decisions and reactions. Creating a time delay between the operating control and the reaction in the system that is being controlled is not without risk, since this can lead to moments during which the driver does not necessarily have full control over the vehicle. The size of these time delays has not been investigated. A common expression for the two types of speed-dependent steering mentioned above is **progressive steering**.

**Longitudinal control**

The requirements that need to be imposed on an operating control for lateral control have their equivalents for acceleration and braking systems, although the spatial working range of both the conventional accelerator pedal and brake pedal is less than that of the steering wheel, which is why alternative accelerator and brake operating controls do not require a working range of the same size as that of the steering operating control.

It is stated in earlier chapters and sections that force-control of the brake pedal is optimal with regard to braking control. It is desirable to transfer this system feature to an alternative brake operating control. The design of the accelerator pedal with its position control is also good. Consideration should also be given to the possibility of transferring this characteristic to alternative operating controls.
5.2 Operating controls for lateral control of the vehicle

Apart from the conventional steering wheel, there is also a range of alternative manually-controlled steering operating controls.

Conventional steering wheel

The steering wheel in an ordinary car functions in a way that is “obvious” to most people. Turning the steering wheel in clockwise direction causes the car to turn to the right, and vice versa. A given deflection of the steering wheel corresponds to a given deflection of the front wheels of the car in accordance with a linear relationship (see Equation 1 on page 13), in which the amplifying factor $k$ is normally about 0.05 when the full deflection of the steering wheel in one direction is 2 revolutions and the full deflection of the front wheels is 1/8 revolution. The low amplification $k$ manifests itself in parking places where tight turns need to be made; a good deal of use has to be made of the steering wheel. The low amplification is comfortable out on the motorway, on the other hand, as only small movements of the steering wheel are needed to perform an overtaking manoeuvre, for example, or simply to follow the road. The feedback present in the steering wheel may be highly significant according to previous discussions.

Steering wheel with amplified steering servo

A steering servo with amplified servo-effect can make it possible for a person with muscular weakness to drive a car. One effect of amplifying the steering servo-effect is that, the more pronounced the lightening, the less natural is the residual feedback in the steering wheel, since the mechanical connection to the steering mechanism is reduced. It is advantageous to be able to retain the steering wheel when adapting a vehicle, on the other hand, since many drivers will be used to driving with an ordinary steering wheel. In the case of drivers with poor trunk stability, the steering wheel can actually help the driver to maintain his/her balance. The design of the steering wheel and the transfer function of the conventional steering system offer advantages in view of the conflict between the small working range (small amount of steering work) and high precision.

The most common adaptation of the steering operating control is a combination of amplified steering servo-effect and a steering wheel spinner, which permits single-handed control of the steering wheel.

Mini steering wheel

A mini steering wheel is a small steering wheel with a diameter of between fifteen and twenty centimetres equipped with a small steering wheel spinner or other handle for single-handed control (see Figure 10). The advantage of this design is that the natural handling of an ordinary steering wheel is largely retained. The entire range of deflection of the front wheels is equivalent to between six and eight revolutions of the mini steering wheel, and the transfer function to the front wheels is linear, as for the ordinary steering wheel. Steering movements are transferred from the mini steering wheel to the front wheels, either via an electro-hydraulic or mechanical system to a steering servo, or via an electronic system and servomotors directly to the steering mechanism. No mechanical coupling is present between the mini steering wheel and the steering mechanism of the car, and accordingly no natural feedback is provided to the driver via the mini steering wheel.

High-amplification steering wheel

It is possible to amplify the deflection of the steering wheel so that a relatively small steering wheel deflection produces a large deflection of the front wheels, which may be helpful if the driver has impaired mobility. This means that a steering wheel deflection of +/- 90 degrees, for example, corresponds to the full deflection of the front wheels. This reduced working range is clearly associated with a risk in the sense that the accuracy reduces and the car can start to pitch and become unstable.

Mechanical-hydraulic lever steering

There are solutions available in which steering is performed with a lever mechanically connected to the valves in the car’s steering servo. The lever can be designed in a variety of ways, but is attached as a rule to a shaft running in the longitudinal direction of the car close to the floor. In order to turn, the lever is moved so that rotation occurs about the shaft to which the lever is attached, by analogy with steering wheel control. The working range is small compared with that of an ordinary steering wheel and a mini steering wheel. (See also the section entitled, “Effects of system dynamics on tracking performance”).

Because the lever is mechanically connected to the car’s steering servo, the transfer function is uncontrolled without a controlled progressive function, which should be present when the working range of the lever is as limited as it is in this case. It is not unusual for lever control to involve a time delay between the deflection of the steering wheel and the front wheels, because the steering servo does not work effectively for this type of steering. The consequences of this are probably a greater amount of mental workload and risks related to the fact that the steering servo is unable to keep up with excessively rapid steering movements (Zarrugh & Miller, 1982). No natural feedback is provided in the lever other than the operation of the valves. By connecting an operating control directly to the valves of the steering servo, a given deflection of the operating control causes
a certain force to act on the front wheels in one direction or the other. As a result of this, the deflection of the wheels is the sum of all the forces which influence the front wheels. If this were to be a sudden skid, for example, which caused the front wheels to lose their grip, there is no guarantee that the front wheels will follow the steering movements of the lever. In the absence of any movement and inertia, the front wheels will assume full deflection for even a small deflection of the lever, in accordance with a system order one.

**Electro-hydraulic lever control**

By causing the output signal from the control lever to be electronic, and by controlling the oil flow into the steering servo of the car via a control system with the output signal from the control lever as the reference value, and with a value on the steering deflection as the true value, electro-hydraulic steering probably improves significantly the possibilities for handling the lateral position of a vehicle compared with mechanical hydraulic steering. The greatest benefit is that a given deflection of the operating control when stationary will always correspond to a distinct deflection of the front wheels. It is also possible to filter the input signal to the steering servo and adapt it to the speed. This solution also lacks natural or active feedback, however, which allows the lever to be moved more rapidly than the speed with which the steering system is able to cope.

**Electro-mechanical lever control**

It is possible to connect a servomotor directly to the steering column of the car. This servomotor can then be controlled via an operating control system according to the same principles as for electro-hydraulic steering.

### 5.3 Operating controls for longitudinal control of the vehicle

Operating the accelerator pedal in an ordinary car does not require a lot of force, although the braking function does require considerable force. Electronic or hydraulic servos (actuators) are used to obtain sufficient force to operate the brakes, and in some cases also the accelerator, with alternative operating controls. Compared with the steering system, these actuators are required to operate over small distances, and the acceleration and braking systems have no inertia, as a result of which these systems are probably relatively rapid without significant time delays.

**Conventional accelerator and brake operating controls**

If the control characteristic of conventional operating controls is transferred directly to alternative operating controls, a small working range is required for acceleration (compared with steering). A non-existent working range would be required in principle for braking. In the case of drivers with muscular weakness, it is then necessary for the force required to operate the operating control to be adapted to their strength. At the present time, however, both the accelerator and the brake are converted to position-controlled operating controls if the adaptation is of an electronic or hydraulic nature, whereas, if the adaptation is mechanical (with a direct mechanical connection to the conventional operating controls), the operating modes (position or force) correspond to the way in which the ordinary operating controls are used.

![Figure 7](image-url)  
*Figure 7  Mechanical accelerator and brake. The white arrow corresponds to the brake function, and the black arrow to the accelerator function (from Betjeningshjelpmidler i bil, © SINTEF Unimed, Oslo).*
Mechanical lever-controlled accelerator and brake

See Figure 7. Mechanical accelerator and brake operating controls enjoy the advantage that the installation is simple, and that a large proportion of the natural operation of the accelerator and brake is retained. Movement patterns that are normally used for the legs can also be used for the arms, so that familiarization with the mechanical accelerator and brake operating controls is easy if the driver has previously driven a car equipped with a foot-operated accelerator and brake.

The disadvantage of mechanical operating controls is that the same work required to operate conventional operating controls must also be performed with hand operating controls. The greatest problem is associated with the brake, which often requires more strength than a normal person has available in his/her arms. In order to overcome this problem, the brake servo-effect can be amplified, and the gear ratio in the operating control can be applied in accordance with the lever arm principle.

Electronic and hydraulic lever-controlled accelerator and brake

See Figure 10. For electronic and hydraulic lever-controlled operation of the accelerator and brake, the lever is connected via electronics/hydraulics to one or two electronic or hydraulic servos which control the accelerator and the brake. These servos can be subdivided into servos with positional feedback and servos with force feedback.

- Servos with positional feedback (typically hydraulic servos)
- Servos with force feedback (mainly electronic servos in this particular case)

The choice of servo type can be adapted with advantage to the item to be controlled. A (force-controlled) brake pedal would be simple to control using a servo with force feedback, whereas the steering could be controlled using a servo with positional feedback. This would make the transfer function between the operating control and the signal to the servo easy to design, since little account need be taken of how the position of the brake pedal changes as the braking force is applied.

A servo with force feedback which acts on the brake exerts a certain amount of force, which produces a transfer function for the brake corresponding to that of the conventional brake pedal (Figure 8). A servo with positional feedback takes no account of the natural force-

![Figure 8](image-url) *Transfer function between force acting on brake pedal and braking effect.*

![Figure 9](image-url) *Qualitative graph illustrating how the braking effect in most cases varies with the deflection of the operating control for a position-controlled brake operating control.*
assistance of the brake, but causes the brake pedal to move for a certain distance. This means that the transfer function is as shown in Figure 9.

A system with a linear transfer function is easier to learn to operate, which leads to quicker reaction times and better results. Active feedback should be present in the system in order to transfer the control characteristic of the brake pedal to an alternative lever operating control.

It is clearly possible to control the brake using a servo with positional feedback, although this requires the transfer function to be adapted to the movement of the brake pedal. All the servos used in the vehicle adaptations studied in conjunction with this project were servos with positional feedback. In one case, the transfer function for the brake had been adapted to the movement of the brake pedal.

**Accelerator and brake ring**
The use of an accelerator and brake ring on a conventional steering wheel is an alternative to the electronic levers described above. Such rings are installed behind (brake) and in front of (accelerator) the steering wheel and can be operated in this way without having to remove the hands from the steering wheel. These operating controls are normally electronic and function in the same way as electronic lever-controlled accelerator and brake operating controls. A disadvantage of these operating controls may be that the task of steering interferes with the tasks of accelerating and braking.

**5.4 Combined operating controls**
It is desirable to design and combine the operating control in such a way that operating both the primary and secondary operating controls (turn indicators, lights and radio, etc.) is as simple as possible while driving the car. A common combination is a hydraulic accelerator/brake and a mini steering wheel (see Figure 10).

Some operating controls and combinations of operating controls are better than others, in the sense that they are easier to learn, present little risk of mixing up the control tasks, and promote a rapid reaction time. The joystick is a combined operating control comprising electro-hydraulic or electro-mechanical lever-controlled steering, accelerator and brake functions, about which more can be read in the following Chapter.

All these solutions have their advantages and disadvantages. It is important for the design of the primary operating controls to suit the driver’s needs and resources. It is important to bear in mind that they must be simple to use, minimize the risk of confusion and facilitate the driver’s ability to react rapidly.

![Figure 10](image_url) **Figure 10** Car equipped with a mini steering wheel and hydraulic accelerator and brake.
6 Design and control characteristics of the joystick

This Chapter describes the design and control function of a joystick system in general terms. Joystick is used to denote an operating control with two combined functions for, in this case, the lateral and longitudinal control of a car. The content is to some extent general, however, for all contexts in which joystick control is encountered. The Chapter also describes the three joystick systems for vehicle adaptation that are available on the Swedish market. Their manufacture is based on the content of earlier Chapters.

6.1 General facts about joysticks

Design

The first thing to cross your mind when you hear the word joystick is the primary operating control in a fighter aircraft or the control lever for the computer game in your lounge at home. This is a partially correct image of the type of joystick intended here. One major difference, however, is that the speed of an aircraft is not controlled with the joystick, as is the case for car control. The two degrees of freedom of the joystick are used instead to control the angle of attack and roll, i.e. steering in two dimensions.

A (4-way) joystick is a lever which has two degrees of freedom, fore-and-aft and from side to side. The joystick can be used, for example, for simultaneous control of acceleration (reverse or forward), braking (forward or reverse) and steering (from side to side) in a motor vehicle. The lever is fixed at a single point, normally in accordance with the principle of a ball-and-socket joint, which gives the lever its two degrees of freedom in accordance with Figure 11.

The design of the joystick handle varies with the area of application. In aircraft, where the operating control is gripped with the entire hand, the grip is ergonomically designed to fit the hand. In those cases in which small, precise movements and adjustments are made, the joystick is controlled initially with the fingers, without the whole hand gripping the operating control. The joystick is often narrower and shorter in such cases, with a smaller grip for the fingers.

The major difference between these two alternative embodiments is that the operating control is operated with the arm (arm-operated) in the case of the heavier joystick, whereas, in the case of the thinner joystick the operating control is operated with the hand and the fingers (hand-operated). People normally have better fine motor control in the fingers than in the arm, whereas the strength in the arm is greater than in the fingers. This means that the applications differ for the two different embodiments.

If there is a requirement for fine motor control, the natural choice of joystick in accordance with the above is the hand-operated joystick, whereas the choice falls on the arm-operated joystick if strength is required. This is not the whole truth, however, and another aspect must be considered: the working range of the joystick acts against the freedom of movement of the operator. Let us assume that a driver with pronounced muscular dystrophy is to control a car with a 4-way joystick. Such a person has very poor, if any, strength in his/her arms. The only alternative in this case is a hand-operated joystick. The spatial working range for a joystick that is held between the fingertips is significantly smaller than for an arm-
operated joystick. The smaller working range means that there is less space available for controlling the whole of the acceleration, braking and steering dynamics of the vehicle. This imposes considerable demands on the driver’s fine motor control and co-ordination capacity. The force-related working range, on the other hand, is not limited by the design of the joystick, but by the operator’s strength and by the sensors in the joystick.

Feedback
The passive feedback in a joystick usually consists of spring-assistance, which means that the joystick attempts to revert to a neutral position, and in some instances frictional resistance, too. In the case of driving a car, the (passive) feedback means that the car will neither accelerate nor turn if the lever is released. It will apply the brakes a little, on the other hand, in order to prevent the car (which is fitted with an automatic transmission) from beginning to move without the driver holding the joystick. More or less advanced passive feedback can be achieved to support the operator in his control task, although the feedback must be active in order to provide the operator with information about the actual status of the system. The following are some of the reasons for the absence of active feedback in today’s joystick systems for car driving:

- A joystick with active feedback requires development and installation costs for which no funding is available at the present time.
- Knowledge of the value of active feedback is insufficient. Developers, installers and users are not aware of the opportunities that active feedback can present for road safety and comfort.
- The National Road Administration’s Code of Statutes contains no provisions in respect of active feedback (see the Chapter “Legislation and standards”), and the meagre accident statistics that are available do not point to an increased risk of accident for disabled drivers.

One problem associated with feedback is that the drivers concerned have very low strength resources. This imposes major requirements on the levels of the feedback forces.

Working range
The working range for a joystick is defined either by a spatial range (angle-controlled joystick) or by a force-related range (force-controlled joystick), within which the joystick can be operated to control a system. The dynamic of the controlled system is critical for which type of joystick provides the most appropriate operating control. The working range for an angle-controlled joystick is limited by the available spatial range, whereas that for a force-controlled joystick is limited by the available force or strength. The two types of joystick are discussed in greater detail below.

6.2 Angle-controlled joystick
An angle-controlled joystick has angular deflection as the input signal to the system controlled by it. This is the most common variant found in all types of joystick systems, ranging from lifting crane operating controls to controls for computer games and, of course, the primary means of control for cars (Haslegrave, 1985; Haslegrave, 1986; Ulrich & Grandel, 1985). The working range of the angle-controlled joystick depends on the length of the joystick and the maximum angular deviations in its two degrees of freedom. If the joystick is finger-operated or hand-operated, the mobility of the fingers and the hand also limits the available working range of the joystick.

Control characteristic for lateral control
The Chapter entitled “Alternative primary operating controls” discusses the conflict between a small working range and high precision. The very small working range of a finger/hand-operated angle-controlled joystick can lead to problems when the entire dynamic of the system is to be controlled. As already mentioned, this poses a problem in a control system of order zero, because a given deflection of the joystick is required to correspond to a given deflection of the front wheels. In the best case, the maximum angular deviation from the central position available for driving a car is slightly more than 20 degrees, and often less (according to the joystick adapters, this figure is limited by driver mobility). If constant amplification is present between the deflection of the joystick and the deflection of the front wheels, the amplifying factor must be $k = 0.5$ (see Equation 1 on page 13) in order to give access to the entire working range of the front wheels. This means that large movements are not required in order to make tight turns at low speeds, but that it is also more difficult to control the lateral position of the car at higher speeds. The manoeuvre, which required a steering wheel deflection of 20 degrees with an ordinary steering wheel, requires a deflection of 0.6 degree for this joystick. With a 10 cm long joystick, the required movement is 1.0 mm compared with the full deflection range of 7 cm. As already mentioned, this narrow working range or high amplification can lead to overcorrections in critical and demanding situations.

A couple of different means of compensating for the tight working range of the lever operating control are offered by speed-dependent low-pass filtering and speed-dependent amplification between the joystick deflection and the front wheel deflection (see the Chapter “Alternative primary operating controls”). In the case of
joystick control, compensation of this kind is necessary to permit the vehicle to be driven safely at all speeds. The type of compensation that attracts the greatest practical recognition is speed-dependent low-pass filtering and a speed-dependent reduction in the amplification between the deflection of the joystick and the front wheels, which is known as progressive control in vehicle adaptation circles.

**Control characteristic for longitudinal control**

As already pointed out for lever-controlled acceleration and braking, the working range is not a problem. On the other hand, it is not obvious how the transfer function for the brake can be achieved. The most natural approach for an angle-controlled joystick is for a given angle to correspond to a specific braking effect in accordance with a linear system of order zero. The feedback for the brake, which at the present time is in the form of passive spring-assisted feedback, could be modified according to previous suggestions. Passive feedback could reflect the braking effect based on a model of the braking system, although active feedback would be the ideal solution. The most natural approach is for the transfer function for acceleration to be designed according to the same principle as the ordinary accelerator pedal with system order zero, which is the case of the joystick systems in use today.

**6.3 Force-controlled joystick**

A force-controlled joystick uses the force applied to the operating control as the input signal to the controlled system. The joystick can be either rigid or moving. This type of joystick need not have the appearance described at the beginning of the Chapter, since a joystick with non-existent or little movement does not require a large spatial working range.

A rigid joystick has only the passive counter-force in the operating control as its feedback. Rigid joysticks are not encountered all that often in the literature relating to the equipment of motor vehicles with joystick control, and they are also not installed as operating controls in adapted vehicles. Roger Koppa et al. (1980) conducted experiments with, among other things, a rigid joystick in conjunction with their evaluation of different types of operating control for vehicles adapted for disabled drivers. A force-controlled joystick could nevertheless offer an alternative to today’s ordinary angle-controlled joysticks.

**Control characteristic for lateral control**

If investigations were to show that drivers with muscular diseases have better dynamics in their strength than in their mobility, a force-controlled joystick could reduce the problem of too little mobility in the hands of these drivers.

Another interesting question is how to design the transfer function. A linear relationship would be ideal, provided that the driver’s force dynamic is sufficient. A problem associated with this design, which has already been discussed above, is that, if a force must correspond to a given angle in the front wheels, then an amplitude-dependent time delay will exist between a change in the deflection of the joystick until the front wheels have turned.

**Control characteristic for longitudinal control**

The same discussion in previous sections also applies to acceleration; the dynamic is not regarded as a problem. There is space for improvement as far as braking is concerned, however. Force control with a linear transfer function would be a good alternative for the joystick. The brake dynamic is relatively large, and there is no inertia in the braking system, which is why a given brake deflection produces an immediate reaction in the braking system and a given retardation of the vehicle. The inherent dynamic of the vehicle obviously causes certain time delays, although no account is taken of this here. Active feedback in the joystick could reflect the braking effect in such a way that a given applied force (forward) always corresponds to a specific braking effect, which may be desirable for drivers with severely impaired strength.

One example in the case of accelerator control is when the speed of the vehicle is fed back as an angle. A given force gives a specific acceleration, which gives a specific speed under given conditions. This speed in turn gives a specific angle in the joystick. If the traffic conditions change (uphill section, etc.), the speed is reduced and the joystick changes its angle. In order to maintain the speed (and the angle), a larger force must be applied to the joystick, which increases the accelerator setting; this occurs naturally as the joystick attempts to move in the opposite direction in relation to the force exerted on the operating control (Eckstein, 1997). Another alternative is for the joystick to be rigid, and for a forward or rearward force always to give a certain acceleration or deceleration.

**6.4 Combination of angle control and force control**

It is possible to combine angle control and force control in a single joystick. One variant could be to cause the accelerator and brake to be force-controlled, while the lateral control is angle-controlled. This would be advantageous in the sense that it would not be possible for any spatial interference to occur between lateral and longitudinal vehicle control.

It is also possible to combine force control and angle control within the same type of control movement. For
example, the lateral control can be controlled with angle control within a range of front wheel deflection as large as that used in normal traffic, whereas force control can occur at the periphery of the working range to support very tight turns.

6.5 Conventional joystick systems

There are three joystick systems for use for vehicle adaptation in Sweden, of which two are commercially available. See Appendix 1 for outline diagrams showing how joystick systems are connected to a car and details of the information flow between the car and the joystick system.

VS 500 JS: Electro-hydraulic/mechanical system

This system is manufactured by Hand Pro AS in Norway, and it is installed in cars in Sweden by Anpassarna Gunnérius AB. The design of the joystick can be studied in Figure 13. See also Appendix 2. This joystick is angle-controlled with simple passive feedback provided via the rubber gaiter fitted around the shaft of the joystick. By using different gaiters, or by filling them with different materials, different degrees of rigidity can be achieved in the joystick (passive feedback).

Analogue signals are sent from the joystick to a control unit. With reference to the joystick deflection, the actual front wheel deflection and the speed, etc., and by using analogue signal processing, control signals are generated here for the electronic/hydraulic servos that control the steering, acceleration and braking in accordance with a system of order zero. The brakes are controlled with an electric servo with positional feedback mounted on the brake pedal of the car, and the transfer function is not specifically adapted to the movement/force dynamic of the brake pedal. The accelerator, too, is controlled with an electric servo with positional feedback. The control signals for steering are sent to hydraulic valves, which in turn regulate the flow of oil in a steering servo. The steering system is progressive, in the sense that the amplification in the transfer function between the deflection of the joystick and the deflection of the front wheels reduces with the speed. The control unit is programmed with the speed at which this progressive function must commence and with the degree of speed dependence. Low-pass filtering (damping of the steering system) can also be entered.

The steering wheel and its airbag are removed in this adaptation, although the steering column is left in place, which can reduce collision safety. The steering wheel can be installed simply with a special device to enable non-disabled persons to drive the car. The other equipment does not affect the ability to operate the accelerator and brake pedals.

Digidrive II: Electro-mechanical system

This system is manufactured by EMC in the USA, and it is installed in cars in Sweden by Autoadapt AB. See Appendix 2. The joystick has spring-assisted return, which gives a specific perception of the central position for steering and accelerating/braking. The steering system is progressive, in accordance with the same principle as the VS 500 JS. The system is entirely dependent on electric servos with positional feedback combined with digital technology. A reversing electric servo with force feedback is directly connected to the accelerator cable and the brake pedal. The transfer function for the brakes is linear, which is preferable for angle-controlled operating controls. An electric servo with positional feedback is directly connected to the steering column via a toothed wheel. The electric servos are designed to cope with handling the car even if its original brake servo and steering servo were to cease to function. It is also possible for non-disabled persons to drive a car fitted with this joystick equipment, because the steering wheel is retained and accelerating and braking are possible independently of the adaptation. The fact that the steering wheel and its airbag are retained means that the passive safety is greater than when the steering wheel is removed. The adaptation possibilities of the joystick system are limited to the required rigidity of the spring-assisted return and the distinctiveness of the progressive function. One interesting function of the steering system is that the servo motor produces a noise, the pitch of which varies with the speed of operation of the motor, which in turn gives the driver an indication of how the steering system reacts to different steering movements. Auditory feedback is able to a certain degree to replace the tactile feedback that is present in a conventional steering wheel.

PVM: Electro-hydraulic system

This system was designed by Autoadapt AB (known as Beram at the time), which also installed it in cars. See Appendix 2. The system has since been superseded by Digidrive II. The joystick has spring-assisted return, all signal processing takes place digitally, and the power sources which act on the accelerator, brakes and steering are hydraulic servos. The transfer function for the brakes is not specially adapted to the natural force dynamic of the brakes. The progressive nature of the steering extends only to speed-dependent low-pass filtering of steering manoeuvres (damping of the steering system). The advantage of this system was that the adaptation possibilities for joystick control and the transfer function for the steering had undergone considerable development. For example, it was possible to adapt the transfer function individually for right and left turns, which may provide an advantage for persons with different mobility in the two directions.
7 Driving a car with a joystick

This Chapter analyses the task of driving a car with the help of the aforementioned commercially available joystick systems. The use of the joystick is also discussed in terms of active and passive safety.

7.1 Information flow and feedback

One consequence of the design of joystick systems today is that the exchange of information between the driver and the car is reduced and distorted in comparison with the way in which standard cars function. Today’s joystick systems lack active feedback, and their function and the design of the joystick operating control are perhaps not optimal. How does this influence the driver’s control of the vehicle, and what are its possible effects on safety?

Lateral control

The problems associated with joysticks appear to be most complex for lateral control. In order to achieve lateral control, the driver performs a combination of open loop control and tracking. The speed with which movement patterns are initiated and the quality of the result depend on several factors reported in the Chapter “Mental resources and manual control of dynamic systems”.

With a low-pass filtered joystick system, it is possible to produce the same reaction in the car with different control movements. More alternatives produce a longer reaction time in the driver. The joystick system has a built-in amplitude-dependent and frequency-dependent time delay, which increases the requirement for anticipation, which increases the mental workload and the reaction time. The lack of tactile feedback makes it more difficult for the driver to learn how the system functions, which can lead to less well-adapted movement patterns.

In order to facilitate the tracking task, it is important

• for the driver to obtain information about the status of the system continuously and in a natural and undistorted fashion without a noticeable time delay;
• for the system dynamic to be favourable with regard to the time delay, band width, amplification, compatibility and system order.


The lateral position of the vehicle is estimated with the eyes, but also with the sense of touch and the sense of balance. A joystick driver does not sense disturbances via the joystick in the way that other drivers sense them via the steering wheel, as a result of which no unexpected disturbances are perceived before the vehicle reacts by changing its course or speed. The joystick does not feed back any information about the actual status of the steering system. The angle of the joystick provides information about where the front wheels should be, although this is neither dependable nor adequate. Changes in the deflection of the front wheels or their grip on the road which depend on external factors are obtained via the steering wheel, but not via the joystick. Amplitude-dependent time delays in the system mean that the driver is placed under a greater mental workload and reacts more slowly, which, in conjunction with high amplification within the joystick system, can cause the system with feedback between the vehicle and the driver to assume doubtful stability characteristics in a demanding situation.

Longitudinal control

It appears probable that the information which contributes to providing the driver with a correct perception of his speed is a combination of auditory, tactile and visual information. The role of the steering wheel is to enable the driver to relate his steering movements to the reaction of the vehicle and to determine the speed of the vehicle from the extent to which and the speed with which the vehicle leans. Given that the joystick system has a time delay, lacks active feedback for lateral control and is low-pass filtered, it may be more difficult for the driver to form an impression of the speed of the vehicle from the relationship between joystick movement and the reaction of the car.

The perception of acceleration does not differ from that when driving with a conventional accelerator pedal, since no change takes place in the way of operating the accelerator with the joystick. The perception of the braking effect should also not differ, because the brake pedal does not feed back the braking effect.

The angle control of the braking function in the joystick harmonizes poorly with the mental image that kinetic energy is caused to decelerate with a counter-force. It is also more difficult rapidly to find a specific position rather than a specific force, because a position is given by starting and stopping a movement; this is a task that requires timing. In order to create the best conditions for operating the brakes in spite of this, the transfer function from the joystick deflection to the braking effect should be linear.

Interference between accelerator/brake and steering control

There is a risk of the occurrence of spatial interference between lateral and longitudinal control, because the joystick has a common pivot point for both lateral and longitudinal control, and no active feedback is present.
which can make the controls more distinct. This problem can be illustrated by the following example. Imagine that you are driving a car with a joystick. You are driving in a curve, and an elk walks out onto the road at the same time as an oncoming vehicle is approaching. You are obliged to make a rapid, controlled braking manoeuvre, followed by an evasive manoeuvre to the left, which in this case is assumed to function well with a conventionally equipped car. What difficulties could present themselves to a disabled driver driving a joystick-controlled car? The movements of the joystick that need to be performed are illustrated in the series of illustrations below (Figure 12).

Moving the joystick rapidly from the accelerator to the brakes without changing its lateral position calls for precision, as does executing an evasive manoeuvre while maintaining an unchanged braking effort. These control movements take place in accordance with open loop control, and if the actual movement patterns are used and perfected frequently for many different situations, then they will presumably work well under normal conditions. In this case, however, where no time is available for closed loop control while moving the operating controls, it is not so obvious that the braking manoeuvre and the evasive manoeuvre will be problem-free. Corrections to the manoeuvre are presumably made in positions a, b and c below, although not in the course of movements between them, since these are performed rapidly in accordance with open loop control. If corrections are made, these take the form of reflex actions which can result in overcorrections. However, the low-pass filtering helps to reduce the effect of these on the steering to a certain extent.

Regardless of the operating control used, if considerable attention must be paid to one of the control tasks, the others will be neglected. In the case of an evasive manoeuvre with a conventional operating control, this may mean that the driver is so preoccupied with steering that he locks the brakes without reacting. It is difficult to brake effectively and turn at the same time in an emergency situation, due to insufficient mental resources. With a joystick in a corresponding situation, the task of steering is associated with a greater risk of influencing the braking task than with a conventional operating control because of spatial interference. Instead of locking the brakes, they could vary between not being applied at all and being locked. This in turn means that the driver may be exposed to a greater risk of losing control of the vehicle.

It is not only lateral and longitudinal control that can interfere with one another. Unintentional movements performed by the driver, or to which the driver is exposed, can clearly influence his/her control of the joystick. Rapid movements of the car, for example caused by strong gusts of wind, can be propagated to the driver and on into the joystick, and this in turn can result in an unintentional manoeuvre. It is important, therefore, for the driver’s seat (usually an electric wheelchair) to be securely mounted in the car, for the driver to sit securely in the wheelchair, and for the part of the body used by the driver to operate the joystick to be sufficiently strong or to have sufficient support.

### 7.2 Personal adaptation of joystick system

The adaptation possibilities available for joystick systems differ from one manufacturer to another, although the available possibilities for adaptation are:

- force required to operate the joystick
- length of the joystick operating control
- size of the working range
- control directions for accelerating and braking
- design of the progressive function for lateral control (amplification reduction and filtering) and when it is to occur.

![Figure 12](image-url)

**Figure 12** Sequence of movements in accordance with: a. Accelerate and turn to the right. b. Move from accelerator to brakes, maintaining a constant turn to the right. c. turn to the left, maintaining constant braking.
The possibilities for adapting the joystick system for different drivers increase the chances of these drivers being able to drive safely and without discomfort, although at the same time the adaptation is more complicated if there are many opportunities for making personal adaptations. In the absence of a generally accepted method for assessing how an adaptation must be executed in order to meet the needs of disabled drivers as closely as possible, it is not easy to make an adaptation of an excessively flexible joystick system. The adaptation must be executed in such a way that it will function correctly in all traffic situations to which the driver may be subjected. To take one example, pronounced low-pass filtering may be comfortable, since jerky control movements will not be propagated into the vehicle, yet at the same time the vehicle is difficult to handle when rapid reactions, decisions and manoeuvres are called for.

7.3 Active and passive safety
Active and passive safety are two fundamental concepts in the context of road safety. Active safety is safety on the move, and high active safety is associated with a low risk of collision or driving off the road. Passive safety is another word for collision safety, and passive safety is high if the risk of injury in a collision is small.

A consequence of joystick drivers’ limited strength and mobility is that many primary and secondary operating controls are positioned close to the driver (see Figure 13). In a number of cases, a secondary operating control (sounding the horn, operating the turn indicators, etc.) is positioned around the head so that it can be controlled by head movements, blowing or sucking, or shoulder movements. All the primary operating controls and most of the secondary operating controls are operating controls that need to be reached while on the move, and as such must be positioned within reach of the driver. Other operating controls which handle separate functions for the disabled driver must also be positioned at a distance such that they can be reached when the car is stationary. The driver’s functional disability means that these tend to be within the same area as the other operating controls. Another consequence of the equipment is that the steering wheel is removed in many cases, as can be seen in Figure 13.

Passive safety
Passive safety is dependent on many factors, primarily in the vehicle, for example deformation zones, seat design, side impact beams in the doors, airbag, position of extra equipment (telephone and control panel for various supplementary functions) and the position of alternative operating controls, etc. In a collision at 50 km/h, the driver may be subjected to forces in excess of 20 g, which means that a person weighing 75 kg would weigh 1.5 tonnes at the moment of impact. It is thus of the greatest importance for the car not to contain any parts with which the driver can make contact. Common serious injuries in collisions are caused by the steering wheel and the steering column, which cause injuries to the skull and the upper body. In order to deal with these injuries, most modern cars are fitted with an airbag.

Figure 13  Driver’s position in a joystick-equipped car (Joystick system VS 500 JS).
The fact that several operating controls are positioned close to the driver when adapting a vehicle for joystick control, there is a considerable risk of the driver striking these in a collision. That is why the vehicle adapters try not to position any operating controls directly ahead of the driver, and to execute the construction and surfaces of the operating controls and their surfaces so that the risk of injury in a collision is as small as possible. The surfaces should be smooth, without sharp edges and projecting components, and the mounting for the operating control should be designed to give way readily if the driver is thrown against it. The steering wheel and any airbag can be removed to give the driver valuable space, although the steering column is left in place and can constitute a safety risk in the event of a collision. It would be desirable, therefore, also to remove the steering column in joystick-equipped cars, although this would make it more expensive to reinstate the car to its original condition, and without a steering wheel the car cannot be driven by anyone other than the joystick driver. There is no legislation to regulate any of the above, and this is the subject of further discussion in the Chapter “Legislation and standards”.

People with functional disabilities which involve impaired strength and mobility are particularly vulnerable in a collision situation. These persons are more “fragile” than non-disabled persons and suffer injury more easily. This should be taken into account when designing the driver’s position in a vehicle adapted for a disabled driver.

**Active safety**

In broad terms, active safety depends on the interaction between the driver and the vehicle. One important quality of the driver is his ability to handle the vehicle and the surrounding traffic situation in such a way that the risk of accidents and near-misses is as small as possible. The important characteristics of the vehicle are its dependability, reliability and design so that the driver’s control is facilitated as much as possible. How is active safety affected by the joystick equipment? The joystick system may require more concentration than conventional operating controls, which may impair the active safety. On the other hand, joystick drivers are presumably well aware of their limitations and possibilities, and they accordingly adapt their driving behaviour to a far greater extent than non-disabled drivers in order to reduce the risks. This is referred to as compensation.

Because of the reduced quantity of information that flows from the car to the driver via the operating control, there is a risk of the active safety not being as high as in a conventional car. The reduced working range of the joystick with its reduced accuracy can also have negative consequences for safety. Practically all the disadvantages of the joystick system that have already been mentioned can affect active safety in a negative sense.

What happens if part of the joystick system fails? A joystick system consists of an operating control, a control unit, actuators and couplings between them. The following measures are normally adopted to make joystick systems as safe as possible:

- The “brain” of the system (the control unit) is duplicated, and the two supplementary units are active at all times while on the move. Only one of the units is actually responsible for control, although if a fault occurs in it, the control function is switched automatically to the other unit. Alternatively, a signal is given and the driver must switch units manually.
- All sensitive electronics are screened from electromagnetic interference.
- Any hydraulic servos are supported by an accumulator reservoir or an emergency pump with a separate battery, which is connected automatically if the hydraulic system ceases to function as intended.
- Any electric servos are capable of powering the brakes and steering without the help of the car’s hydraulic system. The motors may also be fitted with a duplicate set of copper wire windings.
- Emergency braking is possible at all times, regardless of the foot brake system.

The above safety systems are not required under any legislation. The reason for their existence is that the vehicle adapters wish to guarantee that the systems work, and that their customers must be able to depend on their cars.

Bearing in mind the reduced stability of the drivers concerned, it is important from the point of view of active safety for them to be provided with sufficient support to enable them to sit stable in relation to the joystick.

### 7.4 Identification of problems in manoeuvring joystick-controlled vehicles

Problems can be identified in three areas in respect of the joystick systems in use today: (1) The design and working range of the joystick operating control. (2) The information flow between the driver and the vehicle via the operating control. (3) Power sources acting on the accelerator, brakes and front wheels. The following problems can be identified in these areas:

- **Time delay in the steering system**: Because it is possible to move the joystick at a speed faster than the ability of the rest of the steering system to react, an amplitude-dependent time delay is introduced in rapid manoeuvres. This time delay is a result of the combination of a lack of inertia or active feedback in the joystick and insufficiently fast steering servos. It is unclear how large or serious these time delays are.
• **Difficulty in learning how to brake:** The brakes are angle-controlled without feedback to reflect the braking effect, and in most cases the transfer function is non-linear, with the result that the task of braking appears to be more mentally challenging than necessary.

• **Interference between primary driving tasks:** This effect is caused by the fact that the operating control is angle-controlled in the lateral and longitudinal sense about the same pivot point, and that no information about the reaction of the system to control movements is fed back to the operating control.

To what extent do these problems and effects influence the ability of disabled drivers to handle a car safely and without discomfort? The background examined in this report can provide some answers to the above questions, although the answers must still be verified through empirical studies. Few manoeuvring tests have been carried out, and no useful results are available today to enable the significance of the risks listed above to be determined. It is accordingly difficult to know what effect the problems associated with joystick systems have on safety and comfort, or how the drivers compensate for the problems.

The unfavourable working range, time delay and absence of active feedback revealed in the theoretical demonstration of the aforementioned problems could result in joystick drivers swaying more than non-disabled drivers in conventional cars during and shortly after rapid and demanding manoeuvres, becoming more tired and in general not being able to perform such advanced manoeuvres. If the drivers have experience of conventionally equipped cars, the drivers should already be aware of these problems to some extent, since these drivers will have a reference to which to relate the joystick system. A questionnaire survey and an empirical study were carried out in the context of this project, in which experienced joystick drivers participated in a manoeuvring test.
8 Legislation and standards

8.1 Type-approved vehicles
Passenger cars offered for sale within the EU are normally type-approved when they leave the factory. This means that they conform to the technical regulations applicable throughout the entire area of the EU, and that they can be imported into other EU countries and used without the need for registration inspection in each country. If any alteration is made to the construction or equipment of the car, however, the car must then undergo registration inspection. After modification, the car must meet the EU regulations affected by the modification. If the car does not meet the EU regulations after conversion, an exemption certificate may be granted by the Vehicle Standards Division of the Swedish National Road Administration in Borlänge, subject to the submission of special reasons to justify the need for these modifications to the car. The exemption certificate permits the modifications to be approved in accordance with other regulations, such as the Swedish motor vehicle regulations and standards, etc. The exemption certificate means that the modified components need not be tested in respect of their collision safety or active safety in certain cases. If, however, equipment which has undergone collision testing and has been approved is available, then this equipment must be used in the first instance.

8.2 Who may drive cars?
In view of the fact that functional disabilities, diseases and injuries exist in every variation and degree, it is difficult to specify which individuals may or may not drive a car. The Code of Statutes of the Swedish National Road Administration states that, “Disease or impaired function of the organs of motion such as to prevent a motor vehicle from being driven safely in traffic shall constitute grounds for withholding a driving licence.” The following paragraph states that the grounds specified in accordance with the preceding paragraph shall not be considered to exist if the functional impairment can be compensated for by an orthopaedic prosthesis or technical devices installed on the vehicle (VVFS 1998:89). Since 1986, driving licence regulations in Sweden have been governed by an RU Directive (EEC 91/439, 1991).

8.3 Requirements in respect of alternative primary operating controls

Positioning and installation of alternative operating controls
There are no rules setting out where alternative operating controls may or may not be positioned. The rules which could be applied specify the positioning of operating controls in such a way that they constitute the smallest possible safety risk in the event of a collision (ECE, 1994). This means that the operating controls should not be positioned close to and directly in front of the driver. These rules are not strictly applied, although the adaptation companies nevertheless endeavour to position operating controls in such a way that they would constitute the smallest possible risk of injury in a collision.

Requirements are imposed on the installation of operating controls and other extra equipment. Fixings and bolts must be dimensioned and fitted in such a way that there is no risk of their breaking or working loose as a result of vibrations or other influences under normal driving conditions. Little consideration is given to passive safety in an adapted car.

Design of operating control
It is advisable to design the operating control so that there are no sharp edges or projecting corners, although there are no specific requirements for vehicles adapted for disabled drivers.

Manoeuvrability
The Code of Statutes of the Swedish National Road Administration imposes certain requirements on manoeuvrability:
- The braking system shall exhibit functional reliability under normal driving conditions (TSVFS 1985:14).
- The steering shall give the vehicle good directional stability and light and easily controlled steering (TSVFS 1985:20).

Few requirements are imposed on manoeuvrability. The problems outlined in this report have not been the subject of any comments by the vehicle inspectors who were questioned or by the personnel concerned at the
Swedish National Road Administration, and this is reflected in the above requirements. It is not possible for a vehicle inspector to establish whether it is possible for the driver of the vehicle to operate the vehicle correctly with the aid of the vehicle adaptation. There are thus no requirements in respect of whether the driver must be able to handle the vehicle at all speeds and in all conceivable situations. These requirements are instead imposed by the driving test examiner to some extent.

**Safety systems**

A system as advanced as the joystick system demands rigorous safety systems in order to be able to guarantee the safety of the driver and any passengers, although it is still the case that no detailed requirements are imposed on the part of the Swedish Motor Vehicle Inspection Company. The Swedish Motor Vehicle Inspection Company imposes requirements in respect of safety, although these do not cover specific types of system or the scope of any safety systems.
9 References

Alm H: Driving simulators as research tools. DRIVE II project V2065 GEM. 1995.
Trafiksäkerhetsverket: Trafiksäkerhetsverkets föreskrifter om bromsar på bil och släpvagn som dras av bil (TSVFS 1985:14). (Regulations of the Swedish Road Safety Administration in respect of the brakes on cars and on trailers towed by a car).
Tunberg A: Active steering makes the driver and car a safer team. Saab Automobile AB. Trollhättan. 1991.


Vägverket: Vägverkets föreskrifter om medicinska krav för innehav av körkort mm (VVFS 1998:89). (Regulations of the Swedish National Road Administration in respect of medical requirements for holders of driving licences, etc.).


Outline diagrams of the connection of two different joystick systems to a car

**Figure 1:** Outline diagram of how the Digidrive II joystick system is connected to the original system of the car

**Figure 2:** Outline diagram of how the VS 500 JS is connected to the original system of the car