Manoeuvrability characteristics of cars operated by joysticks

A manoeuvring test

Joakim Östlund and Björn Peters
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This report was commissioned by the Vehicle Standards Division of the Swedish National Road Administration. The aim of the report was to identify shortages and potential risks of vehicles operated by joysticks designed for drivers with severe disabilities, especially concerning the human-machine interaction.

A small group of drivers with severe disabilities are able to drive a car provided it is fitted with a joystick for acceleration, braking and steering. Owing to the design of the joystick, which consists of an angle-operated lever fastened at one point, and the lack of natural feedback from the brake system and front (steering) wheels, the task of driving can be unnecessarily difficult and arduous. Above all, three risks can be identified: (1) The lack of feedback from steering causes the driver to make faster movements of the joystick than the servounit can manage, thus causing time delays in the steering system. (2) Since the joystick is angle-operated and the transfer function of the brake is not always optimal, it may be difficult to handle the brake in a controlled and comfortable way. (3) The most obvious risk is that the accelerator/brake control and the steering control may influence each other (interference), mainly since it is not possible to provide tactile separation of the control directions of the joystick.

A manoeuvring test was carried out by five joystick drivers and a control group at Mantorp Park in the county of Östergötland. The possibilities of carrying out fast lateral manoeuvres and fixed controlled decelerations with the joystick were evaluated. Furthermore, a possible interference phenomenon was studied among joystick drivers. The results partly verified the identified risks, even so it was not possible to link the results to traffic safety consequences in an adequate way. Consequently, it is not known whether cars equipped with joysticks for severely disabled drivers create a risk from the traffic safety point of view.
This report was written at the request of Jan Petzäll, at 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 review of the current knowledge. The project was initiated by Björn Peters, a researcher at the Swedish National Road and Transport Research Institute (VTI). Björn was involved mainly in the design of questions in connection with the questionnaire survey and the manoeuvring test at Mantorp Park.

The report presents the results of a manoeuvring test carried out at Mantorp Park during the winter of 1998, in which drivers with severe disabilities and a control group of drivers without disabilities performed three different manoeuvring tests.

The introduction is a summary of the review of current knowledge which formed part of this project. The design of the experiment was essentially developed jointly between myself (Joakim Östlund, Research Assistant at the VTI), Björn Peters and Sven-Åke Lindén, Research Engineer at the VTI.

I am very grateful to Björn Peters, Sven-Åke Lindén and the other individuals who participated with their cars adapted for disabled drivers in the experiment at Mantorp Park. I should also like to thank Staffan Nordmark, sponsoring editor at the report seminar, Jan Petzäll (Swedish National Road Administration) and Anpassarna Gunnér AB and Autoadapt AB, who introduced us to the joystick drivers.

1999

Joakim Östlund, Research Assistant the VTI
Compared with conventionally equipped cars, it is more difficult to manage advanced and fast manoeuvres in cars controlled with a joystick. In December 1998, a manoeuvring test was carried out on a motor-racing track where five persons with severe disabilities, seated in their electrical wheelchairs, drove their own cars equipped with joysticks.

The possibility of driving a car
Certain persons with severe disabilities are able to drive a car if it is controlled with a joystick. They then recover an essential part of their mobility, which may contribute to increased quality of life. But what possibilities are there for driving safely? Three tests were conducted to compare the manoeuvrability of cars equipped with joysticks and a conventionally equipped car.

The following conclusions can be drawn from two braking tests and an evasive action test:
1. It is more difficult to perform fast and controlled decelerations with a joystick. Decelerations may be uneven and end with a jerk, but were effective in every case.
2. It is difficult to perform fast lateral manoeuvres with a joystick. It seemed difficult to turn fast enough.
3. Lateral control (steering) and longitudinal control (accelerator/brake) influenced each other above all in fast joystick movements (interference).

Shortcomings
The lack of feedback normally transmitted to the driver in a conventional car via steering wheel and pedals most likely contributes to the difficulties observed in driving a car with a joystick. The design of the joystick as a lever, mounted at one end in a ball-and-socket joint, also contributes to the fact that the lateral and longitudinal controls interfere.

Suggested improvements
By redesigning the joystick to reduce the risk of interference and introducing active feedback in the braking and steering mechanism, the possibilities of driving a car with a joystick can probably be improved.

Traffic safety
There are no statistics or other signs that disabled drivers in vehicles designed for disabled drivers are involved in more traffic accidents than drivers with no disabilities. From this manoeuvring test, it is not possible to draw any conclusions regarding cars equipped with joysticks and traffic safety.
1 Introduction

1.1 Humans and technology

1.1.1 Target group
The drivers who drive cars equipped with a 4-way joystick for acceleration, braking and steering are severely disabled persons with seriously impaired strength and/or mobility. There are approximately fifteen persons in Sweden who drive with a joystick. This group of people finds it difficult to cope with many everyday situations, due mainly to their severely impaired capacity to move of their own accord. A joystick-controlled car gives these persons a very valuable opportunity to transport themselves over longer distances, to some extent without the need for personal assistance. They are able to meet their transport needs without having to call upon transportation services for disabled persons.

1.1.2 Joystick design and working range
A (4-way) joystick is a lever which has two degrees of freedom, forwards/backwards and from side to side. When driving a car, it is used to control acceleration (forward or reverse), braking (forward or reverse) and steering (side-to-side) simultaneously. The braking function is in a forward direction in most cases, because the forward motion of a body as the result of heavy deceleration must not cause the braking effect to reduce or be turned into acceleration. 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 as illustrated in Figure 1.

The joystick is gripped with the fingers, rather than the whole hand, and is controlled with a combination of finger, hand and arm movements. The joystick is highly sensitive due to its small working range (about +/-20°) and the absence of any “feel” in the joystick – it lacks natural feedback. It is returned to center with spring assistance only. An important ability required of joystick drivers in order to be able to handle a joystick is sufficient fine motor control and sensation in the fingers.

1.1.3 Power sources and control unit
The power sources used to control acceleration, braking and steering with the help of a joystick are electric or hydraulic servos with positional feedback. The servos are usually installed independently of the vehicle’s original system, so that they act directly on the vehicle’s original pedals and steering column or some other part of the steering system.

A control unit (the “brain” of the system) receives electronic signals from the joystick and the car, which it converts into output signals to the electronic/hydraulic servos. The following parameters are measured continuously and influence the control of the vehicle:
- Joystick deflection
- Speed of the car
- Actual deflection of steering front wheels

![Figure 1](https://via.placeholder.com/150)

Figure 1: Construction of the joystick in accordance with the ball-and-socket principle and its two degrees of freedom. On the left: viewed from the side. On the right: viewed from above.
1.1.4 Transmission functions

In the case of acceleration, the transfer function from the joystick angle to increased acceleration is linear, which agrees with the transmission function for acceleration in a conventional car. In the case of braking, which is power-controlled in a conventional car, it is different. The joystick-controlled brake is angle-controlled rather than force-controlled. Depending on whether the manufacturers of the joystick system have taken account of the natural movement/power dynamics of the braking system, the transmission function is more or less favourable. The ideal situation in terms of the interaction between human and car would be for the braking effect to vary in a linear fashion in accordance with a system of order zero with regard to the joystick angle (Wickens, 1992). In other words, this would be a simple connection between the joystick and the braking effect as shown in Figure 2. In those cases in which no account has been taken of the dynamics of the braking system, a joystick angle is transmitted exclusively according to a linear relationship to a distance for which the pedal is caused to move with the help of a servo. A servo causes the brake pedal to move for a certain distance, regardless of the counter force in the brake pedal. The fact that the brake pedal is force-controlled means that the transmission function is in accordance with Figure 3, which is less favourable. With a linear transmission function, it is easier to control the braking effect in comparison with a non-linear transmission function. This is because, with the linear function, the braking effect increases equally for a given change in the deflection of the joystick, regardless of the angle of the joystick. For the non-linear function, a given angular change causes a greater change in the braking effect even if the braking effect is already relatively high.

**Figure 2** Transmission function between force on the brake pedal or brake operating control and braking effect.

**Figure 3** Qualitative graph showing how the braking effect varies with the joystick angle if the power source is a servo motor.
The transfer function for the steering is the most complex. Given that the working range of the joystick is +/- 20° in comparison with the working range of the steering wheel, which is about +/- 720° ( +/- 2 revolutions), obvious problems of accuracy arise if there is a direct correspondence between the joystick deflection and the front wheel deflection. A lateral correction on a main road which requires a steering wheel deflection of 20° would require a joystick deflection of only 0.6°, which represents a movement of 1 mm with a 10 cm long joystick. There are three important factors which limit the speed of actuation and the size of actuation, however, which help to make the steering gentle and insensitive to excessively raid steering movements. These are: (1) A given joystick deflection produces a smaller deflection of the front wheels at higher speeds. (2) The steering servo of the joystick system is not so rapid that it is capable of producing deflections of the front wheels at the same speed with which it is possible to perform movements of the joystick. (3) Built-in, speed-dependent low-pass filtering of the steering movements makes the steering less sensitive at high speeds. One of the designers’ intentional consequences of the design of the joystick system is thus that the steering reacts more slowly at higher speeds. This means that time delays are built in, which become more pronounced at higher speeds. This certainly permits the car to be handled in a gentle fashion, although it must be asked what consequences this has when a critical situation arises which demands rapid reactions, decisions and manoeuvres. In the case of rapid lateral manoeuvres, there are times at which the deflection of the front wheels does not correspond to the deflection of the joystick. Time delays between a control movement and the reaction of the system are mentally highly demanding in advanced control tasks, as is the lack of distinctness between control movement and reaction (Wickens, 1992). In other words, the steering is able to work well in normal traffic, but less well in critical and demanding situations. (In Sweden known as the “JAS” syndrome – a lack of compatibility between the operator’s expectations and the feed-back and function at the control device.)

1.1.5 Tactile feedback

In the case of the conventional steering wheel and brake pedal, the driver is able to sense how the car reacts to control movements and the external environment (road conditions, etc.). None of this natural feedback is present in the joystick, which can have negative consequences on driving performance. Suitable passive and, above all, active feedback can support an operator in his control task, although this is something that has not been noted to any significant degree among vehicle adaptation companies and designers of equipment for disabled persons. This may be explained by the fact that so much importance is attached to the need to design a technically functional system, and the drivers themselves may be overlooked as a result of this. Other reasons may be a lack of appreciation of the usefulness of active feedback, or the belief that it is too costly to develop joystick systems with active feedback.

1.2 Problem areas

It is possible to identify two distinct problem areas for joystick systems with regard to the interaction between driver and car: (1) The design of the joystick and its working range. (2) The information flow between driver and vehicle via the operating control. It is possible to point out three potential shortcomings in today’s joystick systems:

1. The lack of suitable feedback makes it possible to perform more rapid control movements with the joystick than the steering servo can keep up with. This leads to time delays in the steering system and a lack of a direct correlation between deflection of the joystick and the front wheels.

2. The brakes are angle-controlled, and the transfer function for the brakes is very often non-linear, which can make the task of braking unnecessarily difficult and demanding.

3. The design of the joystick as a lever fixed at a single pivot-point allows joystick movements for acceleration/braking and steering to interfere with one another.

1.3 Aim

The aim of the manoeuvring test at Mantorp was to investigate differences between the ability of joystick drivers and a control group:

- to perform rapid controlled braking manoeuvres
- to perform rapid and stable lateral manoeuvres
- to perform braking combined with steering

A further aim was to investigate whether the interference phenomenon arises for joystick drivers and, if so, to what extent. On the other hand, the aim was not to evaluate individual joystick systems.

1.4 Hypotheses

In view of the angle control of the joystick systems and the lack of suitable feedback, it was expected that the joystick drivers would find it more difficult than non-disabled drivers to perform rapid controlled braking manoeuvres. It was assumed that this might manifest itself in the form of very heavy braking, with major variations between the individual braking manoeuvres.
The lack of a direct correlation between the deflection of the joystick and the deflection of the front wheels was expected to result in instable lateral control and difficulties in finding the “right track” quickly after a rapid lateral manoeuvre. It was also assumed that the joystick drivers would experience difficulty in performing lateral manoeuvres as rapidly as the control group, due to insufficiently powerful steering servos and the possible uncertainty that the drivers might feel due to the lack of a correlation between the deflection of the joystick and the deflection of the front wheels.

Due to the design of the tested joystick systems and their passive feedback, there was felt to be a considerable risk of lateral and longitudinal control movements interfering with one another in demanding and critical situations. For example, an unintentional steering manoeuvre could result from a rapid braking manoeuvre in a curve.

The hypotheses may be summarized as follows:
1. Rapid, controlled braking manoeuvres by joystick drivers were expected to be heavy, with major variations between individual braking manoeuvres.
2. Joystick drivers were expected to find it difficult to perform rapid lateral manoeuvres, and their lateral control in purely general terms was expected to be more instable than that of the control group.
3. The tasks of accelerating/braking and steering were assumed to be capable of interfering with one another during challenging manoeuvres.
2 Method

2.1 Test subjects

2.1.1 Experiment group
The experiment group was made up of five Swedish joystick drivers, who were contacted via two Swedish vehicle adaptation companies. Three of these drivers were suffering from muscular dystrophy, one had a high spinal cord injury, and one had fibrodysplasia progressiva (see “Explanations and abbreviations”). All the drivers drove their own cars seated in their electric wheelchairs. The drivers were all men aged between 23 and 46 years, had held a driving licence for between 3 and 23 years, and stated that they drove between 17 000 and 35 000 kilometres every year. They had been driving for between 1 and 6 years with their current joystick system. (For a more detailed background to the joystick drivers, see (Östlund, 1999a)).

2.1.2 Control group
The control group was made up of drivers selected to match the joystick drivers with regard to their sex, age and driving habits. The result was five male drivers aged between 24 and 47 years, who had held a driving licence for between 3 and 23 years, and stated that they drove between 15 000 and 30 000 kilometres every year. The control group also included a female driver initially, because a female joystick driver was to have participated in the manoeuvring test, but was prevented from doing so. The results for the female driver are not reported for that reason.

2.2 Technical equipment

Cars
The most appropriate approach in this case would have been to compare the driving performances of disabled and non-disabled drivers with the same model of car, with the difference that only the disabled drivers would drive a car adapted for disabled drivers. This is because non-disabled drivers do not normally use adapted cars in traffic, unlike disabled drivers. It was important for the disabled drivers to use their own cars, since these were individually adapted. Non-disabled drivers are more familiar with driving a number of different cars, and it was accordingly not felt that their performance would be any worse if they were to drive a specially chosen car in the test, although fitted with conventional controls. All the joystick drivers drove Chrysler Voyager (CV) cars of year model 91 or newer with specially lowered floors. Appendices 1 and 2 contain product data sheets for the joystick systems. Appendix 3 contains a product data sheet for another joystick system, although this was not used in this study. The control group drove a Volvo 850 estate. The choice of Volvo as the reference car was justified for the following reasons: (1) The CV with the lowered floor and the Volvo were considered to have similar driving characteristics. (2) The use of the same vehicle for the entire reference group reduced the number of parameters that were difficult to verify. (3) The choice of a common car offered advantages in the sense that the measuring equipment only had to be installed once. (4) No Chrysler Voyager was available for the control group. All the cars were fitted with ABS brakes.

Measuring equipment
The installation of an accelerometer in the cars made it possible to measure the lateral and longitudinal acceleration of the vehicles with a margin of error of 0.005 g using a sampling frequency of 10 Hz. The “g-analyst” measuring equipment used was manufactured by “Valentine Research Inc.” (Cincinnati, Ohio, USA). The measuring equipment had a storage capacity for a maximum of 8 minutes’ data. The data were transmitted via cable to a computer, and a small program (written by Håkan Wilhelmsson of the VTI) was used to convert the data to Excel format. All data processing then took place in Excel.

It is important to bear in mind that steering manoeuvres subject the car to forces not only in the lateral sense, but also in the longitudinal sense. (Imagine that you are driving at 50 km/h and that you suddenly steer to the right. All loose objects inside the car, including your own body, will attempt to move forwards inside the car at an angle to the left). The course for the manoeuvres was defined by cones, and the manoeuvring test was filmed.

2.3 Procedure
The manoeuvring test was conducted during an eight-day period in the month of December, and each subject occupied a whole morning or afternoon session. Those joystick drivers who wished arrived in Linköping on the evening before their test session and spent the night in Linköping. Two joystick drivers took advantage of this opportunity. The joystick drivers made their way to the VTI in their own vehicles, which were parked in the VTI’s vehicle hall. This was done in order to keep the vehicles warm, to make it easy to adjust the measuring equipment, and to allow the driver’s position to be photographed with and without the driver. The next stage required the test subjects to answer a number of questions over a cup of coffee. The questions were classified under
the following headings:
- Driving habits
- Comfort
- Driving characteristics of the car in critical or demanding situations
- Reassurance and confidence

Only the first point was included in the questions that were out to the control group. Once the group arrived at Mantorp Park, the technician parked the van in a position that gave a suitable camera angle. The test subject and the test leader then spent some time practising all the manoeuvres two or three times, depending on how long it took the test subject to understand between which cones he was required to drive and how hard the braking manoeuvres were to be. There had to be no uncertainty about the correct procedure to be followed in the test sessions. In order to reduce the learning effect, the manoeuvres were practiced at speeds 5 km/h slower than slowest speed used in the test session. After completing the practice session, three manoeuvres were performed, as described below. The sequence used, however, was Manoeuvre 1 first, followed by Manoeuvre 3 and then Manoeuvre 2. This sequence had been found to be appropriate because certain parts of Manoeuvre 1 and Manoeuvre 3 were carried out on the same coned section of track.

Manoeuvre 1: Braking manoeuvre in a straight line
See Figure 4 for the manoeuvre layout. The test subjects were required to drive at a speed of 60 km/h along a section of road edges with cones spaced at a certain width apart. When the test leader in the passenger seat gave the instruction “Brake!” the car had to be brought to a halt as quickly as possible without engaging the ABS system and without causing uncomfortable deceleration (to be judged by the drivers, essentially in respect of the rate of deceleration). Each test subject was allowed a maximum of 5 attempts to perform three successful braking manoeuvres. The braking manoeuvres were considered successful if the test subjects were driving at the correct speed at the start of the braking manoeuvre (+/- 2 km/h) and remained in the marked section of track.

Manoeuvre 2: Braking manoeuvre in a curve
See Figure 5 for the manoeuvre layout. The drivers were asked to perform a controlled braking manoeuvre in a curve following the same procedure as for braking in a straight line, although braking in this case was from both 60 and 70 km/h. The intention was to provide a broader spectrum of information. It was not considered that the use of two speeds in Manoeuvre 1 would serve any useful purpose. The curve radius of 71 m would in theory have produced lateral accelerations of 0.40 g and 0.54 g respectively at speeds of 60 and 70 km/h.

Manoeuvre 3: Evasive manoeuvre
See Figure 6 for the manoeuvre layout. The test required the drivers to perform an evasive manoeuvre at speeds of 40, 45 and 50 km/h. The speeds were to remain constant throughout the manoeuvre. As in the previous manoeuvre, the drivers were permitted a maximum of 5 attempts to perform 3 successful manoeuvres at each speed. A manoeuvre was considered to be successful if the initial speed was correct (+/- 2 km/h), if the speed did not fall or rise by more than 5 km/h during the manoeuvre, and provided that the car remained more or less within the marked section of the track. An assessment of whether the manoeuvre was successful was made in each individual case, taking into account how closely the marked course was followed. The most important requirement was not for zero cones to be struck, but rather for the marked course to be followed as closely as possible.

![Figure 4](image_url)  
*Figure 4*  Plan view of the braking manoeuvre in a straight line. The circles indicate the position of the cones, and the broken line indicates the direction of travel of the car.
A few more questions were answered on completion of the test session. The questions relating to reassurance and confidence were repeated, to allow for the possibility that the joystick drivers may have changed their opinion after the manoeuvring test. The test subjects were asked how difficult they had found the manoeuvres, and how well they thought they had performed. Other headings were:

- Cars and joystick equipment: any technical problems, and their opinion on the design of the joystick system (joystick drivers only)
- Any accidents and incidents.

The joystick drivers were allowed to answer these questions in their own cars at Mantorp, so that they could drive home as soon as possible after the test. The control group answered the questions at the VTI. Travel expenses were reimbursed, and each test subject received an additional payment of 500 kronor (£ 36).

### 2.4 Dependency indicators

Both objective and subjective indicators were taken/derived in conjunction with the manoeuvring test. The objective indicators were used to assess the driving performance of the test subjects. Subjective indicators were of interest because they allow a comparison to be made between the joystick drivers’ own perceptions of the possibilities of driving a car with a joystick with the results produced by the objective dimensions. It was also of interest to compare the objective indicators and the subjective perceptions of any problems and their own performance between the joystick drivers and the control group. This served to reinforce the result of the test conducted at Mantorp.

A significance test was carried out with a 1-way ANOVA, in which it was judged to be possible and relevant. The level of significance was 5%. The variation was obtained in the form of a standard deviation.
The measuring equipment allowed curves to be plotted illustrating the lateral, longitudinal and total acceleration. From these curves, it was possible to study indirectly how the drivers handled acceleration, braking and steering.

### 2.4.1 Hypothesis 1

The following objective indicators were derived in order to assess the opportunities for operating the brakes via the joystick, and to compare braking control with that of the control group:

1. The mean value and the variation in the braking time (Manoeuvre 1, Manoeuvre 2). The braking period was measured from the point at which the braking force was 10% of the maximum braking force until the vehicle came to a halt. In line with the first hypotheses, the braking times for the joystick drivers should have varied more than for the control group, and the average braking time should have been shorter due to the generally assumed greater braking force for joystick drivers.

2. Mean value and variation in braking force (Manoeuvre 1, Manoeuvre 2). The braking force generally should have been higher and exhibited greater variation for the joystick drivers.

### 2.4.2 Hypothesis 2

The following objective indicators were derived in order to assess the opportunities for the joystick drivers to handle the lateral position of the joystick-equipped cars in a rapid and precise fashion:

1. Variation in lateral acceleration (Manoeuvre 1). Manoeuvre 1 did not include any lateral manoeuvres, although it was still necessary to perform a lateral manoeuvre if the car deviated from its course. In a situation such as this, it was assumed that the joystick drivers would correct the lateral position of the car less effectively. It was expected, therefore, that the variation between the joystick drivers would be greater than for the control group.

2. Variation in lateral acceleration (Manoeuvre 2). The lateral acceleration of the car was measured during the initial phase of the braking manoeuvre (start of deceleration). Any variation in this between individual tests within the same manoeuvre would point to shortcomings in lateral control. This variation was expected to be greater for the joystick drivers.

3. Mean value and variation in maximum lateral acceleration (Manoeuvre 3). According to hypothesis 2, the joystick drivers’ maximum lateral acceleration should have been lower than that of the control group.

4. Number of struck cones (all manoeuvres). According to hypothesis 2, the joystick drivers should have struck more cones than the control group in all the tests, especially in the evasive manoeuvre (Manoeuvre 3), since this placed a greater demand on good lateral control.

### 2.4.3 Hypothesis 3

The following objective indicators were derived in order to assess the presence of interference between steering and acceleration/braking movements for the joystick drivers:

1. Variation in braking time and braking force (Manoeuvre 1 and Manoeuvre 2) in conjunction with lateral manoeuvres. As a consequence of the anticipated interference phenomenon, more or less advanced lateral manoeuvres should have given rise to changes in acceleration or braking for the joystick drivers. The interference phenomenon was expected to be apparent mainly in Manoeuvre 2 at the higher speed (70 km/h).

2. Variation in acceleration/braking force in Manoeuvre 3. In the evasive manoeuvre, in which high demands were placed on lateral control, it was expected that acceleration and braking would be affected to a greater degree for the joystick drivers.

3. Variation in lateral control (Manoeuvre 1 and Manoeuvre 2). The variation was expected to be greater for the joystick drivers as a consequence of the fact that the movement of the controls during braking could have interfered with the steering.

A further indicator was the number of attempts which the drivers failed to execute correctly. An attempt was regarded as a failure if the speed on entry (Manoeuvre 1 and Manoeuvre 2) or during the manoeuvre (Manoeuvre 3) deviated or varied excessively, or if the driver deviated excessively from the marked course. This assessment was made by the test leader. It was anticipated that the joystick drivers would find it more difficult than the control group to follow the course, although problems of maintaining speed were not expected to arise for any of the groups.

### 2.4.4 Subjective indicators

1. Trust (internal) with regard to the possibility of handling their cars with the adaptations that had been made, before and after the manoeuvring test (joystick drivers only). It was expected that the drivers would possibly feel less secure after the test.

2. Trust (external) with regard to the cars behaving as expected. This question was put to the joystick drivers before and after the test. It was expected that the reassurance may have reduced after the manoeuvring test.
3. Subjective opportunities for handling their adapted cars in a critical and demanding situation. This question was put to the joystick drivers only before the manoeuvring test, and it was of interest to relate these subjective perceptions to the actual driving performances.

4. The part of their transport need that the joystick drivers were able to meet by driving a car themselves. It was expected that those joystick drivers who had registered for the manoeuvring test were themselves responsible for meeting most of their transport needs as drivers in their own cars.

5. How comfortable joystick drivers found driving for longer distances (>50 km).

6. The level of difficulty of the three manoeuvring tests. It was expected that the joystick drivers would find the test more difficult than the control group.

7. Driving performance in the individual manoeuvres. It was expected that the joystick drivers would be more critical of their driving performance, since these drivers were assumed to be less familiar with such advanced driving techniques as those required in the manoeuvring test. This was expected to lead to the joystick drivers being more surprised, performing less well and, in addition, being aware of this.
3 Results

3.1 Hypothesis 1

Braking
A braking manoeuvre can be subdivided into an initial phase (braking effect is increased to the desired level), a stationary phase (braking effect is kept constant) and a final phase (car comes to a halt). This distinction makes it easier to report the results of Manoeuvre 1 and Manoeuvre 2 (braking in a straight line and in a curve).

Braking time in Manoeuvre 1 and Manoeuvre 2
In Manoeuvre 1, there was a significant difference in the braking time, in which the joystick drivers' braking time was just under one second longer on average than that of the control group (Table 1). In Manoeuvre 2, the braking time at 60 km/h was the same as for the test group and the control group. At 70 km/h, on the other hand, the braking time was 0.7 second longer for the control group than for the joystick drivers. The scatter in the braking time was greater for the joystick drivers; the difference was smallest in Manoeuvre 1 and greatest in Manoeuvre 2, at 70 km/h (Table 2). These differences were not significant, however.

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<thead>
<tr>
<th>Table 1</th>
<th>Mean braking times for Manoeuvre 1 and Manoeuvre 2</th>
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<tbody>
<tr>
<td>J.D.: Mean braking time</td>
<td>C.D.: Mean braking time</td>
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<tr>
<td>Manoeuvre 1</td>
<td>5.6s</td>
</tr>
<tr>
<td>Manoeuvre 2, 60 km/h</td>
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<td>Manoeuvre 2, 70 km/h</td>
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<td>C.D.: Standard mean</td>
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<td>Manoeuvre 2, 70 km/h</td>
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<tr>
<td>J.D.: Mean braking force</td>
<td>C.D.: Mean braking force</td>
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<tr>
<td>Manoeuvre 1</td>
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</tr>
<tr>
<td>Manoeuvre 2, 60 km/h</td>
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3.2 Hypothesis 2

Lateral acceleration in Manoeuvre 1
According to Table 5, the lateral acceleration of the joystick drivers varied significantly more than that of the control group in Manoeuvre 1.

Lateral acceleration in Manoeuvre 2
The lateral acceleration and the mean standard deviation for the lateral acceleration for Manoeuvre 2 are set out in tabular form in Table 6 and Table 7. At a speed of 60 km/h, the lateral acceleration at the entry to the curve for the joystick drivers and the control group was centred around the same value. The scatter was four times as great for the joystick drivers as it was for the control group at 60 km/h; this is a significant difference. At a speed of 70 km/h, the standard deviation was on average 0.04 g lower for the joystick drivers than it was for the control group, whereas the distribution was slightly larger for the control group (not significant). According to the radius of curvature, the control group was initially entirely correct in terms of lateral acceleration, whereas the joystick drivers were as much as 0.08 g too low on average at 70 km/h. This difference cannot be explained simply by the fact that the joystick drivers were travelling too slowly; for example, 0.46 g – 0.08 g = 0.38 g in the curve in question corresponds to a speed of 63 km/h instead of 70 km/h. Such large differences in speed resulted in failed attempts.

### Table 4
Mean standard deviations in braking force (stationary phase) for Manoeuvre 1 and Manoeuvre 2

<table>
<thead>
<tr>
<th></th>
<th>J.d.: Standard mean</th>
<th>C.d.: Standard mean</th>
<th>Significant difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manoeuvre 1</td>
<td>0.027g</td>
<td>0.032g</td>
<td>No</td>
</tr>
<tr>
<td>Manoeuvre 2, 60 km/h</td>
<td>0.049g</td>
<td>0.038g</td>
<td>No</td>
</tr>
<tr>
<td>Manoeuvre 2, 70 km/h</td>
<td>0.10g</td>
<td>0.057g</td>
<td>No</td>
</tr>
</tbody>
</table>

### Table 5
Variation in lateral acceleration

<table>
<thead>
<tr>
<th></th>
<th>J.d.: Mean standard</th>
<th>C.d.: Mean standard</th>
<th>Significant difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manoeuvre 1</td>
<td>0.044g</td>
<td>0.0076g</td>
<td>Yes</td>
</tr>
</tbody>
</table>

### Table 6
Initial acceleration, Manoeuvre 2

<table>
<thead>
<tr>
<th></th>
<th>J.d.: Mean value for La.</th>
<th>C.d.: Mean value for La.</th>
<th>Significant difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manoeuvre 2, 60 km/h</td>
<td>0.41g</td>
<td>0.40g</td>
<td>No</td>
</tr>
<tr>
<td>Manoeuvre 2, 70 km/h</td>
<td>0.46g</td>
<td>0.54g</td>
<td>Yes</td>
</tr>
</tbody>
</table>

### Table 7
Scatter in initial lateral acceleration, Manoeuvre 2

<table>
<thead>
<tr>
<th></th>
<th>J.d.: Mean standard for lateral acceleration</th>
<th>C.d.: Mean standard for lateral acceleration</th>
<th>Significant difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manoeuvre 2, 60 km/h</td>
<td>0.061g</td>
<td>0.016g</td>
<td>Yes</td>
</tr>
<tr>
<td>Manoeuvre 2, 70 km/h</td>
<td>0.030g</td>
<td>0.033g</td>
<td>No</td>
</tr>
</tbody>
</table>
Lateral acceleration in Manoeuvre 3
The maximum lateral forces achieved by the drivers on average in Manoeuvre 3 are presented in tabular form in Table 8. At a speed of 40 km/h, the maximum lateral acceleration achieved by the joystick drivers was 40\% lower on average than that of the control group, a significant difference which increased with the speed.

Struck cones
In Manoeuvre 1, none of the drivers struck any cones. In Manoeuvre 2, two joystick drivers occasionally struck several cones on the outer edge of the curve (failed attempt). In Manoeuvre 3, all the joystick drivers struck cones in the majority of their attempts. Only one of the drivers in the control group struck any cones, and on a single occasion. Table 9 lists the total number of cones struck during the entire manoeuvring test for each test subject. The figure in parentheses indicates the number of cones struck during braking in the curve. The results clearly indicated that the joystick drivers struck cones to a much greater degree than the drivers in the control group. The average number of struck cones in each manoeuvre and for each test subject can be studied in Appendix 4 (only manoeuvres judged to be successful during the manoeuvring test are included). Cones were struck almost exclusively in Manoeuvre 3, and the cones that were struck were mainly cones v3, v7, v8, h5 and h6 (see Figure 6).

3.3 Hypothesis 3
Braking time and braking force
See hypothesis 1 for details of the results for the braking time and the braking force in Manoeuvre 1 and Manoeuvre 2.

Acceleration and braking effect in Manoeuvre 3
See Table 10 for the group mean values of the standard deviations for the joystick drivers and the control group drivers in each manoeuvre. The standard deviation, i.e. the variation in acceleration and braking control, for the joystick drivers was on average approximately twice as high as for the control group; a significant difference.

<table>
<thead>
<tr>
<th>Table 8</th>
<th>Maximum mean lateral acceleration for Manoeuvre 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>J.d.: Max. lateral acceleration</td>
<td>C.d.: Max. lateral acceleration</td>
</tr>
<tr>
<td>Manoeuvre 3, 40 km/h</td>
<td>0.26g</td>
</tr>
<tr>
<td>Manoeuvre 3, 45 km/h</td>
<td>0.28g</td>
</tr>
<tr>
<td>Manoeuvre 3, 50 km/h</td>
<td>0.31g</td>
</tr>
</tbody>
</table>

| Table 9 | Total number of cones struck by joystick drivers and control group drivers |
|-----------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| JD1 | JD2 | JD4 | JD6 | JD8 | Meanv. | CD1 | CD2 | CD3 | CD5 | CD6 | Meanv. |
| 34 | 28 (4) | 8 | 15 | 19 (7) | 21 | 0 | 0 | 0 | 1 | 0 | 0.2 |

<table>
<thead>
<tr>
<th>Table 10</th>
<th>Variation in acceleration/braking force for Manoeuvre 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>J.d.: Mean standard (acceleration/braking)</td>
<td>C.d.: Mean standard (acceleration/braking)</td>
</tr>
<tr>
<td>Manoeuvre 3, 40 km/h</td>
<td>0.047g</td>
</tr>
<tr>
<td>Manoeuvre 3, 45 km/h</td>
<td>0.063g</td>
</tr>
<tr>
<td>Manoeuvre 3, 50 km/h</td>
<td>0.085g</td>
</tr>
</tbody>
</table>
Time during Manoeuvre 3
The time taken by the control group to complete Manoeuvre 3 at 40, 45 and 50 km/h was approx. 6.0, 5.5 and 5.0 s; the corresponding times for the joystick drivers were 0.5 s longer on average. (Uncertainties in the data ruled out the possibility of a significance test).

Lateral acceleration in Manoeuvre 1 and Manoeuvre 2
See hypothesis 2 for details of the variation in lateral acceleration in Manoeuvre 1 and Manoeuvre 2.

3.4 Successful and failed attempts
One of the joystick drivers (JD4) failed all attempts in Manoeuvre 2 as a consequence of an insufficiently high entry speed into the curve. Another driver (JD1) failed the same manoeuvre at 70 km/h for the same reason. One joystick driver (JD8) failed Manoeuvre 3 at 45 km/h, and two (JD8 and JD1) failed at 50 km/h. The reason in this case was that the drivers were unable to maintain sufficient speed or to follow the course without striking several cones. None of the drivers in the control group failed any manoeuvre. All failures were noted as the manoeuvring test continued, and the test subjects were made aware in all cases of whether they had succeeded or failed in an attempt.

One driver (JD8) drove consistently 20% too slowly because of an incorrectly calibrated speedometer. All the attempts were failed as a result of this, although the driver was not aware of the fact. The error was only discovered at the end of the test session. See also Appendix 4.

Table 11 lists the total proportion of failed attempts for all the test subjects. (These attempts were judged to have failed during the test session, and the test subjects were made aware of the judgements). The joystick drivers failed significantly more attempts than the control group.

The results from attempts that were failed because the speed was too low could still be used in certain cases. Driver JD8 drove too slowly consistently, and the measurement values from Manoeuvre 3 at an intended speed of 45 km/h were applied to Manoeuvre 3 at 40 km/h. The number of useable results from each manoeuvre are listed in Table 12.

Table 12 Number of useable results from each manoeuvre.

<table>
<thead>
<tr>
<th>Manoeuvre</th>
<th>j.d.</th>
<th>c.d.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manoeuvre 1</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>Manoeuvre 2, 60 km/h</td>
<td>14</td>
<td>15</td>
</tr>
<tr>
<td>Manoeuvre 2, 70 km/h</td>
<td>5</td>
<td>15</td>
</tr>
<tr>
<td>Manoeuvre 3, 40 km/h</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>Manoeuvre 3, 45 km/h</td>
<td>12</td>
<td>15</td>
</tr>
<tr>
<td>Manoeuvre 3, 50 km/h</td>
<td>8</td>
<td>15</td>
</tr>
</tbody>
</table>

3.5 Subjective indicators
All the joystick drivers apart from one stated that they meet their own transport needs; i.e. they drive their own car if they need to go anywhere. One joystick driver, however, covered 30-40% of his transport needs as a passenger in his own car. (It was possible to drive the joystick-equipped cars with conventional controls). All the drivers believed that it was very comfortable to drive their car, including for distances of more than 50 kilometres.

The joystick drivers’ trust in their vehicles (external) with the equipment fitted to them was high both before and after the test session (average mark 4 on a scale from 1 to 5, where 1 = very low confidence and 5 = very high trust). They indicated the reassurance that they felt with their adapted cars (internal trust) with a mark of 5 (five out of five) on a scale of 1 to 5 (1 = very unsecure and 5 = very secure) before the test session. The average mark fell to 4 after the test session as a result of two drivers reducing the mark to 4, and one driver reducing the mark to 3 (see also Table 13).
The joystick drivers regarded their ability to handle critical and demanding situations as good or very good (marks of 4 and 5 respectively on a scale of 1 to 5). The test subjects rated the perceived difficulty of the three manoeuvres on a scale of 1 to 5 (where 1 = very easy and 5 = very difficult). The joystick drivers assessed the level of difficulty as higher on average than the control group drivers in all the manoeuvres (not significant). The joystick drivers also assessed their own performance as lower on average than the control group drivers in all the manoeuvres (not significant). These assessments were made on a scale of 1 to 5, where 1 was very easy/very poor performance, and 5 was very difficult/very good performance.

3.6 Accidents, incidents and defective joystick systems

A unique factor affecting the joystick drivers was that all the drivers had experienced the joystick system ceasing to function as intended on at least two occasions. Joystick drivers had driven off the road as the result of an electrical fault on three occasions; two of these were due to a defective cable (full front wheel deflection to the left), and the electrical system in the car had failed on one occasion (the car became totally uncontrollable, and it was not even possible to brake). On one occasion, the accelerator stuck open for one of the joystick drivers, although the car was stationary in neutral at the time. On one occasion it was not possible to brake due to icing in a hydraulic piston. Other faults manifested themselves as fault indications, as the engagement of secondary systems and, in three cases, as unreliable steering attributable to worn potentiometers or speed sensors. These accidents did not result in personal injuries.

### Table 13 Subjective indicators

<table>
<thead>
<tr>
<th></th>
<th>JD1</th>
<th>JD2</th>
<th>JD4</th>
<th>JD6</th>
<th>JD8</th>
<th>JD mean value</th>
<th>CD1</th>
<th>CD2</th>
<th>CD3</th>
<th>CD5</th>
<th>CD6</th>
<th>CD mean value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Before the test</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trust (internal)</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Trust (external)</td>
<td>5</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>4.0</td>
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<tr>
<td>Handling critical sit.</td>
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<td>4</td>
<td>5</td>
<td>4</td>
<td>5</td>
<td>4.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Level of difficulty</td>
<td>1.3,3</td>
<td>2.3,5</td>
<td>2.3,1</td>
<td>1.2,3</td>
<td>2.4,5</td>
<td>1.6,3,0,3.4</td>
<td>2.2,3</td>
<td>2.3,3</td>
<td>1.3,4</td>
<td>1.3,4</td>
<td>1.1,1</td>
<td>1.4,2,4,3.0</td>
</tr>
<tr>
<td>Maneuouvre 1/2/3</td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Subjective performance</td>
<td>4.4,3</td>
<td>5.4,4</td>
<td>4.3,5</td>
<td>4.4,3</td>
<td>4.1,1,4.2,3,2,3,2,4,4,4,4,3,4,4,4,5,4,4,5,4,5,4,4,6,4,0,3,6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>After the test</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trust (internal)</td>
<td>5</td>
<td>4</td>
<td>(-1)4</td>
<td>(-1)4</td>
<td>5</td>
<td>3(-2)</td>
<td>4.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trust (external)</td>
<td>5</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>4.0</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>
4 Discussion

4.1 Hypothesis 1
It is possible to identify a method used by the joystick drivers to brake, in particular when the braking function was located towards the front of the joystick. Because the joystick in the tested joystick systems was angle-controlled and so “light” in its action, it was not possible for the drivers to achieve any sort of balanced force in the control such as that which is otherwise achieved with a conventional brake pedal during braking. The joystick drivers were obliged instead to find a particular position for the joystick, in spite of the tendency for the drivers to move forward in their wheelchair during braking. When the drivers started a heavy braking manoeuvre, the joystick was moved forwards so that the car began to brake. This caused the driver to move due to the forward retardation of the wheelchair, with the associated risk of an unintentional increase in the deflection of the joystick. Under gentle braking conditions, a state of equilibrium arises relatively quickly in the body, in the form of a balance between the deceleration of the car and forces which seek to pull the driver back into his wheelchair. The deflection of the joystick depends on this balance, and the position of the joystick also changes if the balance is upset. One consequence of this for the joystick drivers appeared to be that they avoided changing the braking effect during the braking manoeuvres, because to do so would have upset the balance. As a result, the braking manoeuvres ended abruptly, occasionally with some discomfort to the occupants. This did not happen at any time for the control group drivers, which indicates that they found it easier to control the braking effect. A typical (ideal) braking sequence for the joystick drivers is shown in Figure 7. The equivalent braking sequence for the control group is shown in Figure 8.

If the joystick drivers attempted to change the braking effect during the braking manoeuvres, the braking sequence could be irregular, as shown in Figure 9. Note the difference in the braking time: 4.8 sec compared with 7.0 sec.

![Figure 7](image_url) Braking curve for a typical (ideal) braking manoeuvre performed by a joystick driver.

![Figure 8](image_url) Braking curve for a typical (ideal) braking manoeuvre performed by a control group driver.
One of the joystick drivers braked by moving the joystick backwards, which was possible because of the nature of his illness (fibrodysplasia). His body was so rigid that he did not move forwards in his wheelchair, and he thus did not affect the brake in the same way as the other joystick drivers during braking. In his case, braking manoeuvre attempts did not end abruptly.

It was expected that the braking manoeuvres could be heavier in the case of the joystick drivers than the control group, because the joystick systems were sensitive and angle-controlled. The results of braking in a straight line do not indicate any such phenomenon, however, but rather that the joystick drivers braked with less force. When braking in a curve, at 60 km/h, the braking times and the braking forces were approximately the same for both the joystick drivers and the control group. At 70 km/h, on the other hand, the joystick drivers braked more heavily than the control group, which resulted in shorter braking times. This result can be related to the varying degree of difficulty of the braking manoeuvres, in which braking in a straight line was the easiest and braking in a curve at 70 km/h was the most difficult manoeuvre. The more difficult the manoeuvre, the more heavily the joystick drivers braked. The control group drivers braked with about the same braking force in both Maneuver 1 and Maneuver 2, whereas the joystick drivers increased their braking effect in line with the level of difficulty. Similarly, the variation in the braking effect increased more for the joystick drivers in line with the level of difficulty. The differences were not significant, and yet they indicate the possibility that it may be difficult to control the brakes with a joystick.

Visual examination of the braking curves gives a clearer impression than the significance test (see Graphs 1 to 6 in Appendix 5). In purely general terms, the braking time and the braking force appear to vary more for the joystick drivers than for the control group. All the drivers apart from one in the control group consistently exhibited a more distinctive braking pattern than the joystick drivers. When taken in conjunction with the numerical observations, this indicates that the joystick drivers did not have the same high level of control over their braking manoeuvres as the drivers in the control group.

All the drivers who participated in this manoeuvring test had plenty of time in which to prepare themselves for the braking manoeuvres. The outcome could have been different if the drivers had been unprepared, as it is mainly under stressful situations that people exhibit the ability to “take on too much” and perform less appropriate movement patterns. Poorer actuation of the controls takes more time, with a greater associated risk of the driver failing to control his own movements. Less good actuation of the controls could have a greater effect on the result in this case.

The conclusion is that joystick drivers tend to find it more difficult to control their braking in demanding situations than drivers without disabilities. Changes in the braking effect appear to be difficult to perform with a joystick in those cases in which the braking function involves moving the joystick forwards, as a consequence of which the task of braking is more demanding. This explains why the braking manoeuvres may be heavier and may end abruptly.

4.2 Hypothesis 2

It was assumed that the joystick drivers would exhibit poorer stability in their lateral control, and that it could prove problematical to execute sufficiently rapid steering manoeuvres. See Graphs 7 to 12 in Appendix 5 for all the print-outs for lateral control in Maneuver 2 and Maneuver 3.

There was a significant difference in scatter in the lateral acceleration for braking in a straight line; the scatter exhibited by the joystick drivers was greater, in line with the hypothesis.
There was a significant difference in scatter in the lateral acceleration for braking in a curve (Manoeuvre 2) between the control group and the joystick drivers; the scatter exhibited by the joystick drivers was greater. The scatter can be explained, however, by the possibility of considerable variation in the entry speeds of the joystick drivers. As test leader, however, I noted on a number of occasions that the joystick drivers did not always enter the curve correctly, but made a lateral correction immediately before or after entering the curve. This had an effect on the lateral forces acting on the car.

All the joystick drivers encountered problems in the evasive manoeuvre (Manoeuvre 3) in negotiating the coned track without striking any cones. The reason for this was that they were unable to obtain sufficient deflection of the front wheels to follow the track. The drivers attempted to execute the manoeuvre by making as much use as possible of the edges of the track, although in most cases they still struck cones. Because of their ability to perform quicker steering manoeuvres, the control group drivers achieved more than 40% higher lateral acceleration than the joystick drivers. In every case, they executed the manoeuvre in almost all the tests without striking any cones. There may be two possible reasons why the joystick drivers performed insufficiently rapid steering movements:

1. The joystick drivers could not, or were frightened to utilize the whole of the lateral working range of the joystick.
2. The ability of the joystick systems to produce sufficiently large deflections of the front wheels was insufficient. One joystick driver said that he was steering to the full extent available, in spite of which he was unable to complete Manoeuvre 3 without striking cones, which bears out this hypothesis.

A combination of the two reasons mentioned above presumably contributed to the problems in completing Manoeuvre 3.

Furthermore, there was a greater variation between the individual curves for the evasive manoeuvres for the joystick drivers than for the control group drivers (see Graphs 7 to 12 in Appendix 5), which may point to general steering problems during demanding manoeuvres. These problems and point (1) above may have had their origins in the time delays in the steering system and the lack of feedback through the joystick. The lack of a direct correlation between the deflection of the joystick and the reaction of the car may have made the task of steering difficult and mentally challenging in the demanding situations to which the drivers were exposed. These are situations with which the control group in this manoeuvring test experienced no observable difficulties.

4.3 Hypothesis 3

It was assumed that steering would interfere with accelerating/braking for the joystick drivers, and this is what actually happened. In addition to the reason for the interference taken up in the hypothesis, however, interference was also caused by another factor. The two interference phenomena which occurred were:

1. Joystick movements for accelerating and braking interfered with joystick movements for steering because the joystick control was designed as a lever with a single pivot point, in accordance with the hypothesis.
2. Movements in the car were transmitted to the driver’s arm and onwards to the joystick, causing an unintentional manoeuvre to be performed.

An examination of all the print-outs for lateral and longitudinal forces permitted the identification of many instances of interference for the joystick drivers (30% of the manoeuvres judged to be usable), because the interference manifested itself as simultaneous large changes in force in the lateral and longitudinal directions. Similar phenomena did not arise for the control group, however. It is difficult to decide whether the interference can be related to (1) or (2) above. A number of cases in accordance with (2) are obvious, however, and primarily in Manoeuvre 3 when the drivers performed violent steering manoeuvres. They moved forwards in their wheelchairs when they steered, which resulted in the application of a large braking force. See Figure 10, for example.

A distinct pattern in the acceleration/braking curve (Manoeuvre 3), which is particularly noticeable for the control group (see Graphs 13 to 18 in Appendix 5), must not be confused with interference. This pattern has more to do with the fact that, as a car steers, the forces that are generated in the car run at an angle to the driver. This means that force components which derive from lateral manoeuvres are obtained in the curves relating to longitudinal control.

The variation in lateral acceleration in Manoeuvre 1 may be attributable to some degree to the interference phenomenon, although this is difficult to distinguish from problems associated with handling the lateral control. The same problem occurred in Manoeuvre 2, although in this case it was easier to identify simultaneous changes in lateral and longitudinal acceleration.

In Manoeuvre 3, the joystick drivers operated the accelerator/brakes significantly more frequently than the control group. This difference can probably be linked to the fact that the joystick drivers experienced difficulty in not operating the accelerator or brakes during the evasive manoeuvre in Manoeuvre 3. One possible consequence
of this is the extra half-second on average required by the joystick drivers to complete Manoeuvre 3 at each speed.

One phenomenon encountered on three occasions by one of the joystick drivers was that the lateral acceleration in the curve prevented the driver from holding his arm in a position such that he was able to steer to the right. He could not steer through the curve, and he was forced to stop the car quickly.

4.4 Other results
The joystick drivers stated that they themselves took care of most of their transport requirements, although they were also able to use a transportation service for disabled persons or to travel as passengers in their own cars. This probably indicates that they depend on their cars and feel confident about their ability to handle them. This is in spite of the fact that all the joystick drivers had experienced their joystick failing to function as intended on at least two occasions. A note was taken during the test of whether the test subjects were particularly pleased with their performances or were particularly shaken by a certain incident. Joystick drivers were very satisfied with their braking performance on two occasions in Manoeuvre 1. This may indicate that they do not usually perform smooth and well-controlled braking manoeuvres. The driver who braked in panic in the curve as a result of being unable to steer to the right did not want to continue with the specific manoeuvre. At the same time, however, he did not seem to feel surprised at or particularly shaken by the incident.

It emerged during the question sessions in conjunction with the manoeuvring test that the joystick drivers were able to drive their cars even if their electric wheelchair was not locked securely to the floor of the car. Bearing in mind the weight of a driver and an electric wheelchair, the consequences of a collision could be very serious indeed if the wheelchair was not restrained. What would happen if the wheelchair were to move back by only a few centimetres when the car accelerates? It should be unacceptable for these cars to be capable of being started unless the driver is sitting properly restrained. More recent models were fitted with a warning buzzer which sounded if the wheelchair was not secure when the car was started.

One interesting result of the manoeuvring test was that the joystick drivers found it difficult to maintain a sufficiently high speed at the entry to the curve in Manoeuvre 2. They maintained that it went against their “instinct” to drive at 70 km/h in the curve, a comment that was made by all the joystick drivers. In some cases it was not possible to act against this instinct, which may indicate that joystick drivers avoid risks or uncomfortable situations to a greater extent than drivers without disabilities. Problems in maintaining the correct speed in the curve did not arise for the control group, although the comments made by these drivers in some cases were similar to those of the joystick drivers.

The impression given by the joystick drivers in the course of their journey from the VTI to Mantorp Park was that they drive less impulsively, more cautiously and are generally more relaxed in traffic. Nevertheless, they did not lack self-confidence when driving, and they behaved safely and without fear in traffic.

The fact that joystick drivers adapt their driving style more than drivers without disabilities may be explained by the fact that they are highly dependent on their cars and that, even though the risk of their becoming involved in a critical or unmanageable situation is small, they are not willing to take that risk. Another way of looking at this is that joystick drivers do not take greater risks than able-bodied drivers; i.e. their own physical condition and the adaptations to their vehicles mean that the level of risk

**Figure 10** Example of interference caused to a driver with muscular dystrophy in an evasive manoeuvre.
is the same for them as it is for drivers without disabilities, in spite of the fact that the driving behaviour of joystick drivers is characterized by calm and by a lack of impulsive actions. It may be the case that joystick drivers are obliged to adapt a great deal in order to be able to drive as safely as other drivers. There is a need for further studies to examine in greater detail the ability of joystick drivers (and other disabled drivers) to drive a car safely and without discomfort.

There are no statistics to indicate that disabled drivers with adapted cars are involved in more accidents than drivers without disabilities. Research is being carried out in an attempt to shed light on the subject.

4.5 Experiment group
The number of joystick drivers who registered for the manoeuvring test was so small that it was difficult to obtain relevant results. However, given that the total number of joystick drivers in Sweden was only twelve at the time of the test, the turnout for the manoeuvring test was not bad. Norwegian joystick drivers could also be contacted in order to mobilize a greater number of joystick drivers for further manoeuvre tests in the future. There are around 80 joystick drivers in Norway, which is more than in Sweden. Presumably only those drivers who regarded themselves as being highly skilled in handling their joystick-equipped cars registered for the manoeuvring test. This may have contributed to an excessively positive image of joystick drivers’ ability to handle their cars.

The functional disability of the joystick drivers was caused by three different medical conditions: muscular dystrophy, spinal cord injury and fibrodysplasia. Differences between these individual conditions gave the drivers different levels of ability to drive their cars, which presumably explains the different results between the drivers. Such differences are, of course, interesting in this pilot study, although the small groups of drivers make it impossible to determine the differences and capabilities of the individual drivers with a single manoeuvring test. This was not the aim of the manoeuvring test, which was to evaluate the joystick system for all drivers who drive with an electronic 4-way joystick.

4.6 Tracks
The manoeuvring test was carried out during daylight hours in December, and the wind and weather did their utmost to present all the drivers with varying driving conditions. The road surface was kept free of ice at all times, although snow clearance and de-icing may have affected the width of the track slightly ahead of the curve. The friction of the road surface was considered to be constant for all drivers.

The tracks were marked with cones, and none of the drivers experienced any difficulty in following the track in each test. The cones represented natural obstacles which forced the drivers into the tracks. One phenomenon which was encountered by a couple of drivers was that when they drove into a cone with the front of the car, they braked abruptly. This was a natural reaction, of course, but not a reaction that we sought in the manoeuvring test. Drivers in Manoeuvre 3, therefore, acted contrary to their natural behaviour by not braking in case they drove into a cone directly ahead. This may have caused stress, which in turn may have impaired their performance. An alternative approach would have been to mark the track with a white line instead of with cones. This would have brought other problems, however, such as difficulties in getting the drivers to follow the line in Manoeuvre 3 and to achieve objective performance figures (see also “Measuring equipment”).

The speeds selected for Manoeuvre 1 and Manoeuvre 3 worked well. The entire control group managed to complete these tests without problem at the set speeds, which indicates that the degree of difficulty was not unreasonably high. The joystick drivers managed to complete Manoeuvre 1 in every case, and Manoeuvre 3 at a speed of 40 km/h. Some of the data for Manoeuvre 3 were missing at the higher speeds, because the joystick drivers found it difficult to execute the evasive manoeuvre at higher speeds. The general perception in Manoeuvre 2 was that the speeds involved (60 and 70 km/h) were higher than the speeds at which the drivers would normally drive in such a curve. It was felt that 60 km/h would be a high, although not abnormally high, speed. A speed of 70 km/h, on the other hand, was felt to cause greater problems, and these were actually encountered. The nature of these problems was essentially that the joystick drivers were not able (afraid or not prepared) to drive at such a high speed in the curve. Some data were not available as a result, although the available data still point to an interesting result, which was discussed with a view to getting the joystick drivers to modify their driving behaviour. The manoeuvring test could have been performed differently by relocating the braking manoeuvre to a curve with a large radius of curvature initially, which then reduces. This would presumably have made it easier to maintain a higher speed at the entry to the curve.

4.7 Control group’s car
The choice of car for the control group attracted some criticism during the manoeuvring test. The criticism concerned the weight, height and handling characteristics of the car, which would have favoured the control group according to the critics. A detailed comparison between
the performance of the cars would have to be made in order to establish whether this was the case.

Because of a measurement error, the fact that the Volvo was 19 cm narrower than the Chrysler Voyager cars only emerged after the manoeuvring test was complete. This probably had an effect on the number of cones struck in the evasive manoeuvre test. In spite of this, it was felt that the differences between the cars do not discount the relevance of the conclusions that were drawn from the test results.

4.8 Measurement equipment
Measuring lateral and longitudinal accelerations worked well with the equipment used in the tests. The equipment was positioned beneath the front passenger seat, and it never became detached or failed. The accuracy of the equipment and the sampling frequency were found to be sufficient for the purposes of analysing the force curves. However, one limitation was the inability to derive the speed or position of the car from the acceleration data, which could have provided additional information (apart from struck cones) in respect of how well the coned tracks were followed.

It would have been interesting to measure the deflection of the joystick, steering wheel/pedals and front wheels in order to establish how the drivers operate the primary controls. Unfortunately, this was not possible. Continuous measurement of the lateral position with a so-called “lane tracker” during the manoeuvres would have been desirable and valuable. The VTI has a “lane tracking” system, although the equipment was not available and neither the time nor the resources were available to install the equipment in every joystick driver’s car before each manoeuvring test.

4.9 Subjective indicators and performance indicators
The extent to which joystick drivers believe that driving a car with a joystick works well may be reflected in the sense of confidence that they feel in the opportunities for handling their cars with the adaptation that has been made to the car. All the joystick drivers felt very confident before the manoeuvring test (grade 5), although the grade awarded by three of the drivers fell after completing the manoeuvring test. The reason was presumably that these three drivers were surprised at their ability to perform advanced manoeuvres with their adapted cars. One of the drivers, who did not change his view of his confidence, had practised advanced driving on gravel roads or in areas with restricted vehicular access on a number of occasions. This driver was presumably not surprised, as he was already familiar with the capabilities and limitations of his specially adapted car. This driver was the only joystick driver who had undergone advanced driving training.

On average, the joystick drivers considered that the manoeuvres were 20% more difficult than the drivers in the control group considered, and they felt that they had performed 15% less well than the control group drivers felt they had performed. These differences were not significant, and yet they align closely with the fact that the proportion (aware) of failed attempts was significantly higher on average for the joystick drivers. The fact that the test subjects were aware of their failures probably influenced their perception of how well they had done.
5 Conclusions

The following conclusions can be drawn from the Mantorp Park manoeuvring test:

• In a demanding situation, it may be difficult to execute a controlled braking manoeuvre with a joystick without the braking being heavy and uneven. Problems may occur in particular if it is wished to change the braking effect. This presumably has to do with the fact that the joysticks concerned are angle-controlled and lack appropriate feedback for the braking function. Due to the problems in changing the braking force, heavy braking ends in most cases with a jolt.

• The lack of tactile feedback in the joystick when steering and insufficiently rapid steering systems limit the speed at which a joystick driver can perform rapid lateral manoeuvres. In an evasive manoeuvre which calls for rapid joystick movements and reactions in the steering system, this limitation can have a critical influence on whether the manoeuvre is successful.

• As a consequence of the design of the joystick as an angle-controlled lever with a common pivot point for two functions, demanding manoeuvres present a considerable risk that joystick movements intended for steering will affect acceleration or braking (and vice versa). This can be described as interference.

• Interference can also occur as a result of the movements of the vehicle being transferred to the driver’s steering arm and onwards to the joystick. Intentional joystick movements can thus give rise to unintentional movements, which in turn result in an undesired manoeuvre. This also contributes to the difficulties in changing the braking effect in accordance with the earlier discussion.

• Although time delays in the steering system probably affect the ability to steer a car with a joystick, it was not possible either to demonstrate this or reject it on the basis of the manoeuvring test at Mantorp. See also the second point.

• It is very important for drivers in joystick-equipped cars to be in a fixed position in relation to the joystick in order to reduce the risk of involuntary joystick movements, so that the driver is in an appropriate driving position. This means that:
  1. The wheelchair must be locked to the car in a secure fashion, so that the wheelchair is unable to move in relation to the car. It must not be possible to start the car unless the wheelchair is securely attached.
  2. The driver must be securely strapped into the wheelchair, to ensure correct ergonomics and safety, but above all so that the driver is prevented from moving unintentionally in relation to the wheelchair.
  3. The part of the body used by the driver to control the joystick must be sufficiently strong or sufficiently securely attached that it does not move unintentionally in relation to the joystick.

• The manoeuvring test at Mantorp Park has shown that the ability to control a car with a joystick is not as good as with conventional controls.

It must be pointed out that the results of the manoeuvring test at Mantorp Park cannot be taken as the basis for a more restrictive attitude towards joystick-controlled cars.
6 Suggestions for changes and improvements

There are many possibilities for improving the joystick systems tested in the manoeuvring test. The most important improvement that should be made is to minimize the risk of interference between longitudinal and lateral control. This involves:

1. designing the joystick so that lateral and longitudinal movements of the joystick are separated;
2. designing the joystick so that the driver is not exposed to the risk of unintentional lever movements being performed as a consequence of movements of the car;
3. introducing appropriate feedback in the joystick, in particular for braking and steering, which would help to improve the driver’s perception of the direction of control actuation for each control function.

In purely general terms, the transfer functions, working ranges and forces required for operating the joystick should be individually adapted and should conform to the results and suggestions that have emerged from the research conducted into the manual control of dynamic systems. (For references, see (Östlund, 1999b)). Presented below are two suggestions in respect of the possible configuration of alternative control systems for the joystick system.

6.1 Suggestion for joystick system 1

A radical change in the joystick control would be to redesign it as a small steering wheel, along the lines of certain radio transmitters used for radio-controlled cars. Lateral control is achieved by rotating the steering wheel according to the same principle as the conventional wheel, with the difference that rotation is effected with the fingers and/or the forearm. Longitudinal control is achieved by pulling or pushing the steering wheel forwards or backwards along a straight line. This means that the axis of rotation for lateral control is located in the middle of the control, and that the axis of rotation for longitudinal control is totally eliminated. See Figure 11.

The steering wheel should not be so large that it cannot be operated comfortably and safely with the fingers, for example five centimetres in diameter. The advantage of this design is that the lateral and longitudinal control is more separate than for the joystick, i.e. the risk of interference is reduced. This can lead to considerably simpler vehicle control with shorter reaction times and better control possibilities.

The lateral working range is in this suggestion represented by a range of rotation, which can be utilized

![Figure 11](image-url)
to different degrees by different drivers depending on their mobility and strength. If it necessary for the fingers not to move along the steering wheel, the working range will be approximately half a revolution, which is equivalent to 15 cm. This can be compared with the working range of the joystick, which is approximately half as large.

The brakes should preferably be force-controlled with active feedback, with a linear relationship between the force and the braking effect. The accelerator can also be power-assisted. By controlling the acceleration of the car with a certain force, the physical working load can be reduced, once a specific speed is being maintained, by not applying any force either forwards or backwards (in principle a cruise control system).

For the steering, the transfer function can have a progressive characteristic such that the deflection of the front wheels is dependent on the ratio of the joystick deflection to the square of the speed, which means that the lateral acceleration sensed by the driver is maintained at a constant level for a given deflection of the steering wheel above a certain speed, for example 30 km/h. A constant ratio between the deflection of the steering wheel and the lateral acceleration can permit optimal use to be made of the mobility of the joystick drivers for steering at all speeds. The actual deflection of the front wheels should be fed back actively via the electric servo into the steering wheel in accordance with the above-mentioned ratio between the steering wheel and the front wheels. This makes it impossible to turn the steering wheel more quickly than the front wheels can keep up with, and the deflection of the steering wheel and the deflection of the front wheels always correspond to one another in accordance with the above relationship between the steering wheel and the front wheels. This in turn means that the driver always has a good idea of the position of the front wheels, and that the aforementioned time delays are practically entirely eliminated. If it is not possible to utilize active feedback in the steering, then at least passive feedback should be included in the form of an inertia, which prevents more rapid steering movements than the steering system is capable of keeping up with. It is important to adapt all the forces required to operate the controls to the strength of the driver.

This embodiment and this principle should be suitable for drivers with fine motor skills and good control in their fingers, but who lack strength in their arms. This embodiment is not suitable for drivers with high spinal cord injuries, since these drivers are unable to grip a control of this kind due to the excessively reduced feeling and strength in their fingers.

6.2 Suggestions for joystick system 2

Drivers with high spinal injuries use rotation of the forearm to steer by joystick control, and in most cases they have poor feeling in their fingers. A different design of joystick for these drivers could have the appearance of a joystick, but with feedback and transmission functions in accordance with the previous suggestion. The cruise control function, which is a consequence of the power-assisted acceleration, would relieve the load on drivers with spinal injuries and facilitate the task of driving for them (Peters, 1996).

Drivers with high spinal injuries find it difficult to grip and sense, as already mentioned, and it should accordingly be possible to design the grip of the joystick to suit the hand of an individual driver. An adaptation of this kind would not would not restrict the controllability of the control, since the only movements performed by the driver involve moving the hand from side to side. No rotation takes place in a fore-and-aft sense, and only forces are applied. See Figure 12 for details of control

![Figure 12](image-url)
design. Two alternative axes of rotation are shown in the Figure. In one case (Alternative 1), rotation takes place via the same point as for the conventional joystick. In the other case (Alternative 2), the axis of rotation is positioned along the driver’s forearm, which can give better stability to the lateral control. This embodiment means that, for example if the movements of the car are transmitted to the driver’s steering arm, this will not cause rotation of the controls, since the forces in question are directed through the axis of rotation of the control (no torsional moment is generated). The control is designed to be capable of being operated without the driver having to grip the control (in this case with the right hand).

6.3 Comments on the suggestions
The two alternative suggestions proposed here are not analysed in any greater detail elsewhere. The intention of the suggestions is to show that it is possible to formulate alternative and supplementary solutions for today’s joystick systems. These solutions and suggestions should be capable of simplifying the mobility and increasing the security of many drivers with severe disabilities. If the joystick systems are improved, they may become an alternative for many more drivers with disabilities, at which point it should be possible to reduce today’s very high production costs. The suggestions relate only to the joystick systems. In order to ensure good control over the vehicle, the drivers must also be fixed in relation to the vehicle and the joystick. This will prevent the execution of involuntary movements as a result of movements of the vehicle inducing new joystick movements via the driver’s body.

6.4 Improved collision safety and ergonomics
The steering wheel, together with the airbag, was removed from four of the five joystick-equipped cars used in the tests at Mantorp Park. The steering column was left in position, however, to allow the cars to be reinstated to a condition such that drivers without disabilities can drive them. The steering column could also be removed if the main priority was the safety and comfort of the joystick drivers. This would offer two advantages:
1. Valuable space is made available for the driver and controls.
2. Collision safety is increased, since the steering wheel and the steering column can cause serious injury to the head and upper body in a collision.

If the steering column is not removed, consideration should also be given to not removing the steering wheel and airbag. The section of the steering wheel containing the airbag is retained in certain cases, which provides more space than if the entire steering wheel had been left in place.

6.5 Joystick technology in the automobile industry
Daimler-Benz is in the process of developing a joystick system for commercial use (Eckstein, 1997). This system is not intended for disabled drivers, although the technology could be readily generalized to make it of great benefit to drivers with serious functional disabilities. What distinguishes this system from the systems that were used in the manoeuvring test is the fact that it has active feedback and the transmission functions are optimized to a considerable degree in favour of good vehicle control. Other automobile manufacturers are also aware of this technology and are themselves engaged on projects in the area known as “Drive By Wire”. SAAB was the first company to develop the idea of steering a car primarily with a type of joystick with active feedback (Bränneby, Palmgren, Isaksson, Petterson & Franzén, 1991). This system unfortunately never proceeded beyond the experiential stage, and the project has been discontinued for a number of years.
7 Bibliography


Joystick system VS 500 JS

Joy-stick styresystem
VS 500 JS

Joy-stick styresystem er det mest avanserte hjelpemiddel til bruk i bil for den funksjonshemmede idag. Dette systemet er utviklet spesielt for personer med veldig svake funksjoner, men som har full farlighet, og fin-motorikken intakt.
De beste resultatene oppnås for personer med forskjellige former for f.eks. muskelsyke.

Van-Service as

(The illustration to the original product sheet has been re-edited by the VTI, due to the poor quality of the image)
Joystick system PVM

Joystick/Mini steering wheel

A Beram joystick or mini steering wheel enables a person disabled by restricted movement, or diminished muscle strength, in the arms or legs to drive a car. The normal steering wheel and pedal functions are transferred to the new control system. The Beram control system can be modified or finely adjusted right there in the vehicle, in line with any change in the user's driving skills. Most people can learn to drive a car using a joystick or mini steering wheel. The scope offered by this new control system is virtually boundless.

The limitations are very few.

BERAM
Joystick system Digidrive II

Digidrive II is years ahead of its time and comes standard with features our competition can only dream about!

Joystick Module

The most visible component of the Digidrive II system is the Joystick Module. All driver inputs for controlling Gas, Brake and Steering functions are accomplished with the 2-axis Joystick. The steering axis is side to side with left being left steer and right being right steer. The forward/reverse axis controls the Gas and Brake functions with the direct acting solenoid as no push or pull for brake. The Sensor Module is the method through which the system informs you of its operating mode and displays the function of the sensor systems. The Emergency Backup feature is located on the module and provides manual engagement of the backup systems.

Gas/Brake Servo Motor

The Digidrive II Gas/Brake Servo Motor comes completely assembled and calibrated ready to plug in. This compact, powerful design bolts to the floor of your vehicle so the left of the factory brake pedal and the integral drive arm simply pushes on the brake pedal with no additional mechanical linkages and does not impair brake-to-brake operation of the factory gas and brake pedals. Digidrive II puts you in complete control of the servo communications, "positional feedback" information back to the Computer Module whenever you accelerate or brake using the joystick. No modifications to the factory brake cylinder or booster are required due to the powerful (200 lbs.) force the servo can exert on the brake pedal of your vehicle.

FEATURES

- Directdrive II is the only digital driving system in the world... a computer "Driven by 300" technology allowing accurate microprocessor control usually only found in advanced aircraft. Flight control systemsrequire Safety through Design. The Directdrive II system of control physically isolates the steering from a single joystick interface.
- Eliminates the need for conventional hydraulic backup systems and separate sensor systems. These modifications found in other systems. Your vehicle's gas/brake and steering system is only motor the way the vehicle manufacturer intended.
- Digital technology means faster response, more simulations are accomplished in a few days by our simulation center.

NOTE: Consignment or special orders delivered only in your state, usually within 7 working days after receipt of order. Systems are always in stock.

+ In today's tough economy, "no sale" vehicles are a necessity due to potential scheduling conflicts and lengthy backlogs. Your vehicle's special driving system review, acceleration and brake pedal response fully functional for use byrebuilt drivers. Directdrive II can be deported for rebuilt engine in less than 30 seconds.

If you need assistance with Gas/Brake control ONLY... TURN THIS PAGE FOR OPTIONS
Joystick system Digidrive II

All EMC digital driving controls are truly "state-of-the-art". In other words, Digidrive II has evolved to become the most recent, the most technologically advanced, the most capable driving control system in the world today. And why have EMC driving controls earned this reputation?... because we listen to those people who use our products, those who market our products, and those who benefit from our products. Using innovative design and technological advances, EMC driving controls have evolved to benefit you...today, and into the future.

Steering Servo Motor

This motor is not visible to the driver due to its location behind the dash panel.

The Digidrive II Steering Servo Motor comes completely assembled and calibrated ready to plug in. This compact, powerful design is mounted to the base of the factory steering column under the dash panel of your vehicle, and does not impair the steering operation of the factory steering wheel. The patented "combined" mechanism allows your vehicle's power steering to be fully replaced by the Digidrive II. The new "combined" unit replaces the steering gear and the steering column. Your vehicle will be controlled by the computer, and you will feel the "real" feel of your vehicle without the power steering pump or drive belt.

Computer Module

- Electronic tuning ensures easy operation. All systems, computers, and power steering are completely redundant, and should the computer ever need repair, the system will automatically switch to a backup computer, eliminating the need for additional equipment.
- Diagnostic tools allow your dealer to update software changes from EMC and to print diagnostic reports detailing the operational history of your device. The Computer Module has a number of advanced features, including a built-in vehicle monitoring system, which monitors the vehicle's performance and provides data to the operator.
- Diag precision tools are included in all Digidrive II Computer Modules and enable you to review your personal driving records and make adjustments to your vehicle's settings. The Computer Module can be configured to operate up to 250 different makes/models of vehicles as they become available for Digidrive II.
- Emergency features are standard equipment on all Digidrive II Computer Modules and enable you to react to unexpected situations and maintain control of your vehicle. The Computer Module is designed to automatically activate the emergency features in the event of a collision or other emergency situation.
- Acceptance by Vocational Rehabilitation Agencies in 50 states (except Texas), and the Department of Veterans Affairs, means you can take advantage of possible co-payment help if you qualify for assistance under these programs.

Compact design mounts to the floor between the front seats in all van applications.
Table of struck cones, speed and failed attempts

The table below contains the results of the test subjects with regard to struck cones, initial/maintained speed and failed manoeuvres. The test subjects were made aware of these failures. It was still possible to use certain of these, as well as the results from JD8 (speed consistently too low). See also under the heading “Results”.

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<thead>
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<th>Manoeuvre</th>
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| No struck cones on average | 5 km/h too slow |
| 1-3 struck cones on average | 10 km/h too slow |
| > 3 struck cones on average  | 15 km/h too slow |

Key to manoeuvres in the above table

160: manoeuvre 1, 60 km/h
260, 270: manoeuvre 2, 60 km/h and 70 km/h
340, 345, 350: manoeuvre 3, 40, 45 and 50 km/h
Force curves for all manoeuvres
Graph 6: CD All 15 braking curves
Manoeuvre: 70 km/h

Graph 8: CD All 15 evasive manoeuvre curves
Manoeuvre: 40 km/h

Graph 5: JD Available 5 braking curves
Manoeuvre: 70 km/h

Graph 7: JD All 15 evasive manoeuvre curves
Manoeuvre: 40 km/h
Force curves for all manoeuvres

Graph 17  JD: Available 8 curves for long. control
Manoeuvre 3, 50 km/h

Graph 18  CD: All 15 curves for long. control
Manoeuvre 3, 50 km/h