Research Article

Adam Sowiński*, Tomasz Szczepański, and Grzegorz Koralewski

Car braking effectiveness after adaptation for drivers with motor dysfunctions

<https://doi.org/10.1515/eng-2021-0060>

received December 01, 2020; accepted February 23, 2021

Abstract: This article presents the results of measurements of the braking efficiency of vehicles adapted to be operated by drivers with motor dysfunctions. In such cars, the braking system is extended with an adaptive device that allows braking with the upper limb. This device applies pressure to the original brake in the car. The braking force and thus its efficiency depend on the mechanical ratio in the adapting device. In addition, braking performance depends on the sensitivity of the car's original braking system and the maximum force that a disabled person can exert on the handbrake lever. Such a person may have limited power in the upper limbs. The force exerted by the driver can also be influenced by the position of the driver's seat in relation to the handbrake lever. This article describes the research aimed at understanding the influence of the above-mentioned factors on the car braking performance. As a part of the analysis of the test results, a mathematical function was proposed that allows a parametric description of the braking efficiency index on the basis of data on the braking system, adaptation device, driver's motor limitations, and the position of the driver's seat. The information presented in this article can be used for the preliminary selection of adaptive devices to the needs of a given driver with a disability and to the vehicle construction.

Keywords: manual operating brake, vehicle adaptations, people with disabilities, road safety

1 Introduction

Driving cars by drivers with disabilities usually requires special adaptations [1–3]. These are often devices that make it possible to operate the vehicle using the upper limbs. One of the most frequently used devices is the manual operating brake. It usually takes the form of a lever located in the floor or under the steering wheel, and moving it forward activates the working brake [4,5].

The kinematics and dynamics of the braking lever and the upper limb are very important in the operation of the device adapting the braking system for the needs of people with disabilities. From the biomechanical point of view, the upper limb pressing on the brake lever is in a completely different range of motion than the lower limb pressing on the brake pedal without adaptation.

To illustrate this phenomenon it is worth comparing several typical solutions used for people with disabilities. Figure 1 shows a vertically installed gas/brake device at the driver's seat. The device is a kind of lever. A human pushes one end of it and an arm with a pusher exerts pressure on the brake pedal.

Figure 2 shows the gas/brake device mounted horizontally under the steering wheel. The principle of operation is the same, but this time the lever is placed horizontally, which changes the trajectory of the driver's hand.

Figure 1: Vertically installed gas/brake device in driver's seat.

* Corresponding author: Adam Sowiński, Department of Diagnostics and Servicing Process, Motor Transport Institute, Warsaw, Poland, e-mail: adam.sowinski@its.waw.pl
Tomasz Szczepański, Grzegorz Koralewski: Department of Diagnostics and Servicing Process, Motor Transport Institute, Warsaw, Poland

Figure 2: Gas/brake device, horizontally installed under the steering wheel.

There are also special solutions that allow the braking to be implemented in a different way, for example, with a joystick or other devices. Many of them use the movement of the wrist when the rider cannot move his entire arm. An example of such a solution is shown in Figure 3.

However, the most popular solutions are the first two, presented in Figures 1 and 2. They are installed in most vehicles adapted for people with lower limb dysfunctions. Therefore, in the rest of this article, attention will be focused on them.

When operated with the lower limb, the driver has a relatively high force. At the same time, the bending angle in the knee joint is close to 90° , which makes the lever mechanism relatively insignificant. Meanwhile, when operating with the upper limb, the driver has significantly less force, but the angle in the elbow joint is close to 180° . This causes a lever effect that increases pressure on the brake. As a consequence, the distribution of forces in the upper and lower limbs during brake operation is significantly different [6].

Figure 3: Vehicle control with joysticks.

The above phenomenon is important because the pressure force on the brake jack in the adaptation device depends not only on the force generated by human muscles, but also on the geometric position of the driver in relation to the brake jack and on the kinematics parameters of the adapting device.

The basic geometrical parameter, important from the point of view of the pressure applied to the handbrake jack, is the distance between the jack handle and the driver's shoulder joint. In this space, the driver's arm and forearm must fit, forming such an angle in the elbow joint that it is possible to freely press the brake jack.

The basic kinematics parameter is the distance that the handle of the handbrake jack must travel to achieve sufficient braking force on the wheels of the vehicle. This path will hereinafter be referred to as the brake jack deflection. In general, the smaller deflection distance of the handle causes the smaller influence of the kinematics on the dynamics. It can also be formulated by a condition that is expressed in equation (1):

$$u + r + p < d, \quad (1)$$

where u is the deflection of the handbrake lever, r is the upper arm of the driver, p is the driver's upper limb forearm, and d is the distance of the jack handle from the driver's shoulder joint.

According to the above relationship, the sum of the deflection of the handbrake jack and the arm and forearm of the driver's upper limb must be smaller than the distance between the jack handle and the driver's shoulder joint. This imposes certain restrictions on the distance of the handle from the shoulder joint. If the jack deflects too much, it may result in a small leverage in the biomechanical lever present in the elbow joint. This, in turn, will reduce the force the driver exerts on the brake.

In the case of people with disabilities, paresis of the upper limb, which is operated by the brake by the driver, is a relatively common phenomenon. For this reason, a situation in which too much pressure on the brake jack will be required must not be allowed.

The deflection of the brake jack depends on two factors:

- (a) brake pedal deflection in an unmodified brake mechanism,
- (b) the gear ratios of the adapting device.

The second factor is crucial in the design of adaptive devices. If the ratio is 1, the force required for manual operation will be the same as the force required for application with the foot. This situation is unacceptable because of the lower force generated by the upper limbs.

On the contrary, if the gear ratio of this mechanism is too high, it will cause a large deflection of the brake jack. For these reasons, it is very important to optimize the design of adaptive devices and to control the correctness of their operation and installation.

During the operation of the brake, in the case of using adaptive devices, there are three mechanisms introducing the force transmission:

- (a) hydraulic transmission in an unmodified brake system,
- (b) a lever mechanism in the adaptation device,
- (c) biomechanical transmission in the driver's upper limb.

The hydraulic transmission is usually not modified when adapting the vehicle to the needs of people with disabilities; however, its parameters are important when selecting the parameters of the adapting devices and when selecting the position of the driver's seat. The selection of design parameters to adapt to the braking system to operate with the upper limb will be very important. The gear ratio in the lever mechanism is particularly important. The biomechanical transmission, in turn, can be influenced by the positioning of the chair. An important factor in this case is the distance between the jack handle and the driver's shoulder joint.

It may turn out that there is no brake lever ratio and driver's seat distance that meet two requirements:

- (a) a sufficiently small force to apply a brake lever to the handle,
- (b) a sufficiently small deflection of the jack to provide a sufficiently large biomechanical lever.

There is not much research going on in this regard. What is worse, there are no legal regulations that would impose certain requirements on this type of adaptation devices [1]. Basic documents, such as Road Traffic Law [7], as well as technical conditions of vehicles and the scope of their necessary equipment [8] do not impose any restrictions. Furthermore, the regulation on the scope and method of carrying out technical tests of vehicles [9] does not impose any obligations on a diagnostician in the process of conducting periodic tests.

There are, of course, numerous studies on disabled drivers which mention the need for specialist rehabilitation of people in terms of driving [3,10–13]. They focus primarily on the human being as a driver, on his limitations and needs, and to a much lesser extent on adaptive devices.

We can also distinguish a group of publications on the broadly understood road safety with the participation of people with motor dysfunctions [14–17]. They deal with such issues as the impact of motor limitations on safety, modeling of biomechanical phenomena during a road collision, or social aspects related to the safety of people with disabilities. Unfortunately, there is no

analysis of adaptive devices and their functionality in terms of road safety.

There is also a group of publications on the adaptation devices themselves [4–6,18]. They mainly concern ergonomic aspects and the selection of devices corresponding to human motor dysfunctions or technological issues. However, no research has been carried out on the handbrake in the context of the vehicle braking performance.

It is also worth mentioning the works on periodic technical inspections of vehicles for people with disabilities [2,19]. However, they do not cover a possible procedure for testing the braking performance with the handbrake for a driver with motor impairment of the lower limbs.

To sum up, it is worth emphasizing the lack of research and legal regulations regarding braking efficiency in the case of modification of the braking system for people with disabilities. For this reason, the aim of this article is to present the most important factors influencing the safety when using the manual working brake.

2 Research methodology

The detailed objective of the described research was to check how the car braking efficiency index depends on the following factors: the original vehicle braking system, the adaptation of the braking system, the strength of a person with motor dysfunctions, and the position of the driver's seat.

The braking efficiency rate was used as a measure of the safe operation of the braking system. It is defined by equation (2):

$$z = \frac{\sum T}{P} \times 100, \quad (2)$$

where z is the braking rate for the type of brake tested, $\sum T$ is the braking force obtained from all wheels (kN), and P is the gravity force resulting from the permissible total mass of the tested vehicle (kN).

Considering that the braking force obtained from all wheels is closely related to the braking deceleration, the relationship shown in equation (3) can be formulated:

$$z = \frac{b}{g} \times 100, \quad (3)$$

where z is the braking rate, b is the measured braking deceleration, and g is the acceleration due to gravity.

For M1 vehicles (passenger car) before the date of first registration on 28 July 2010, the minimum braking rate is 50%. After 28 July 2010, the minimum braking rate is

58%. In the tests, the value of 58% was adopted as a condition for the safe operation of the braking system.

The research was conducted at the Motor Transport Institute, with the use of five vehicles equipped with a hand operating brake lever, as an adaptation for people with disabilities. The research included several stages:

- measuring the dependence of the braking efficiency index on the force applied to the brake pedal,
- measuring the dependence of the braking efficiency index on the force applied to the brake lever,
- measuring the force generated by people with disabilities with different settings of the driver's seat.

During the measurement of the dependence of the braking efficiency index on the force applied to the brake pedal, a decelerometer equipped with a brake pedal pressure sensor was used. It allowed for measuring and registering the maximum force on the pedal and the braking efficiency index resulting from the weight of the vehicle and the maximum braking deceleration. The tests were performed on five different vehicles, repeating the measurement for different values of the pressure applied to the brake pedal.

During the measurement of the dependence of the braking efficiency index on the force applied to the brake pedal, a decelerometer was used, this time equipped with a pressure sensor on the brake lever. It allowed for measuring and registering the maximum force on the lever and the braking efficiency index resulting from the vehicle weight and the maximum braking deceleration. The tests were similarly carried out on five different vehicles, repeating the measurement for different values of the pressure applied to the brake lever.

The measurement of the force generated by people with disabilities at different positions of the driver's seat was performed in cooperation with five people with motor dysfunctions of the lower and upper limbs. These people pressed the brake lever with maximum force. The measurement was repeated several times, with different driver seat settings, to vary the distance between the driver's shoulder and the brake lever. A pressure sensor on the brake lever was used for the measurement.

During the tests and their analysis, the measurement of the position of the driver's seat, marked with the letter L and expressed as a percentage, was used. It takes the following values:

- 0% for the position of the seat as close as possible to the steering wheel for which the test driver can press the brake lever,
- 100% for the position of the seat as far as possible from the steering wheel, for which the test driver can press the brake lever,

- intermediate values, in the conducted research equal to 25, 50, and 75%.

This means that for each driver, the measurement of the relative seat position (L) determines a different distance between the seat and the steering wheel, expressed in terms of an absolute measure. It mainly depends on the physical dimensions of the tested driver.

The measurement results and their analysis are presented in the next section.

3 Test results

Figure 4 shows an example of the dependence of the braking efficiency index on the force applied to press the brake pedal, and Figure 5 shows the dependence of the braking efficiency index on the force applied to the handbrake lever. In addition, the gray color shows the values of the calculated proportionality ratio between the braking efficiency index and the force applied to the brake pedal or brake lever, respectively. This factor is represented by equation (4) for the brake pedal and equation (5) for the brake lever.

$$w_{UH} = \frac{z}{F_p}, \quad (4)$$

$$w_{UA} = \frac{z}{F_d}, \quad (5)$$

where w_{UH} is the proportionality factor for the original brake system, w_{UA} is the proportionality factor for a braking system adapted for drivers with disabilities, z is the braking efficiency index, F_p is the force applied to the brake pedal, and F_d is the force applied to the brake lever.

Figure 4: Dependence of the braking efficiency index (z , black color) and a proportion ratio between the braking rate and the pressure on the brake pedal (w_{UH} , color gray) on the force on the foot brake (F_p).

Figure 5: Dependence of the braking efficiency index (z , black color) and a proportion ratio between the braking rate and the pressure on the brake pedal (w_{UH} , color gray) on the force on the handbrake (F_d).

Knowing the values of the coefficients w_{UH} and w_{UA} , it is possible to determine the value of the proportionality coefficient characteristic for the adapting device itself, in such a way that shows the relationship (equation (6)).

$$w_{UA} = w_{UH} \times w_A, \quad (6)$$

where w_A is the proportionality factor for the adaptive device.

The above graphs show the values of forces on the brake pedal and the brake lever to be pressed so that the value of the braking efficiency index reaches a minimum value of 58%. These values result from the design of the braking system, including the brake assist system, and the design of the adaptive system.

Figure 6 presents the comparison of the proportionality coefficients between the braking efficiency index and the force applied to the pedal and the brake lever.

Figure 6: Comparison of the proportionality coefficients between the braking efficiency index and the force applied to the pedal and brake lever for each car.

Black color indicates the operation of the original braking system, gray color indicates a system modified by an adaptive device, and white color indicates the calculated coefficient for the adaptive device itself.

As can be seen from the above drawing, the use of the adapting device slightly reduces the required brake force. However, these are relatively minor changes. Only in the last case the coefficient changes twice, which proves the use of a very sensitive adaptive device (with a significant gear ratio in the lever).

Figure 7 shows an example of the dependence of the force on the handbrake lever (F) on the measure of the driver's seat setting (L) for one of the examined persons with motor dysfunctions.

As it can be seen in the graph above, the pressure applied to the brake lever significantly decreases as the driver's seat is moved away from the brake lever.

A model describing the force of pressure on the handbrake lever by the driver was proposed in the form of the relationship (equation (7)).

$$F_d = F_{\max} - w_L \times L, \quad (7)$$

where F_d is the handbrake lever deflection, $F_{\max}$ is the maximum force at which the test driver can put on the brake lever, L is the measure of the relative distance of the seat from the steering wheel, and w_L is the proportional factor between the force on the lever and the measure of the position of the driver's seat.

It is worth noting that even the maximum value of the force shown in Figure 4 is relatively small and amounts to about 160 N. This phenomenon has been shown in more detail in Figure 8, which shows the maximum force values for various test persons. For comparison, the result for a non-disabled person is also presented.

Figure 7: Dependence of force on the handbrake lever (F) on the measure of the driver's seat setting (L).

Figure 8: Comparison of the maximum pressure force on the handbrake lever for a non-disabled person and for individual respondents.

As it can be seen in the graph above, people with motor dysfunctions can have considerable difficulty in exerting a lot of force on the handbrake lever.

Comparing the dependencies (6) and (7), a model can be proposed that describes the dependence of the braking efficiency index on the parameters characteristic of the car braking system, the adaptive device, parameters describing the driver's force, and the seat position. This is expressed in equation (8).

$$z_A = (F_{\max} - L \times w_L) \times w_{UH} \times w_A, \quad (8)$$

where z_A is the braking rate for a car with adaptation, $F_{\max}$ is the maximum force at which the test driver can put on the brake lever, L is the measure of the relative position of the driver seat, w_L is the proportional factor between the force on the lever and the measure of the position of the driver's seat, w_{UH} is the proportionality factor for the original brake system, and w_A is the proportionality factor for the adapted braking system.

Thanks to this, it is possible to analyze what will be the possibility of safe braking after applying a given adaptive device to a car with given braking system parameters, in the case of a driver with given motor dysfunctions. Figure 9 shows the examples of the results of the dependence of the braking efficiency index on the relative position of the driver's seat for individual tested persons (gray, solid lines) for the Peugeot Partner car. The individual lines represent the examined persons. The field of function is the relative distance between the position of the driver's seat. The black dotted line represents the braking rate limit value below which the braking process is too little intense.

As shown in Figure 6, most of the respondents are able to cause the braking phenomenon at a safe level.

Figure 9: Comparison of the dependence of the braking efficiency index on the relative position of the driver's seat for individual examined persons for the Peugeot Partner car.

Only two people, with the driver's seat far away, may have a problem with this. One person in turn, regardless of the position of the chair, exerts a force slightly greater than required. This state of affairs proves of the correct operation of a given adaptive device in a given vehicle, as well as its universality for people with various degrees of disability.

For comparison, Figure 10 shows a different set of devices.

It can be seen from the chart above that most people are not able to exert enough force on this device. Only for a very close position of the driver's seat the forces are greater than minimal, but such a seat positioning does not have to be comfortable because of other operational activities performed behind the wheel. This is an example of a wrongly selected adaptation device for a given car.

Figure 10: Comparison of the dependence of the braking efficiency index on the relative position of the driver's seat for individual examined persons for the Skoda Fabia.

4 Summary

Based on the presented research results, the following conclusions can be drawn:

1. The braking rate depends on factors such as: the design of the original braking system, the design of the adaptive device, the force of a driver with a disability, and the position of the driver's seat.
2. The ratio used in the adaptation device may increase the braking force caused by a given pressure on the brake lever to a varying degree. The low sensitivity of the original braking system and the low gain of the adapting device may cause that the force required on the brake lever will be too great.
3. People with motor disabilities may have relatively little force to apply to the brake levers.
4. The maximum force applied to the brake lever depends on the position of the driver's seat.
5. With the wrong selection of the adaptation device for a given car and driver, it may turn out that the force exerted on the brake lever will be too weak to cause the braking process of the appropriate intensity.

The above observations lead to the conclusion that adaptive devices in vehicles should be selected taking into account the parameters of the braking system used in a given car, as well as taking into account a given driver with limited motor functions. Certification of adaptive devices may be considered with certain restrictions with regard to the vehicles they can be used on and the disabilities with which they can be used.

References

- [1] Karpiński R, Zysińska M. Uwarunkowania merytoryczno-prawne dotyczące wymagań technicznych oraz zasad dopuszczania do ruchu pojazdów przeznaczonych do kierowania przez osoby niepełnosprawne ruchowo lub do ich przewożenia, *Logistyka*, nr 3/2015; 2015.
- [2] Sowiński A, Zysińska M, Dziedziak P. Badanie techniczne pojazdów po zmianach konstrukcyjnych dostosowanych do korzystania przez osoby niepełnosprawne, *Logistyka*, nr 3/2015; 2015.
- [3] Ucińska M, Stasiak-Cieślak B. Niepełnosprawny kierowca w ruchu drogowym – kompleksowe wspieranie mobilności, *Autobusy*, nr 12/2016; 2016.
- [4] Malawko P, Szczepański T, Świdorski A. Wpływ parametrów urządzeń adaptacji na prowadzenie pojazdu. *Prace Naukowe Politechniki Warszawskiej. Transport* z. 121, s. 233–45; 2018.
- [5] Stasiak-Cieślak B. Procedura doboru urządzeń adaptacyjnych wspomagających prowadzenie samochodu przez kierowcę z niepełnosprawnością. *Prace Naukowe Politechniki Warszawskiej. Transport* z. 121, s. 363–73; 2018.
- [6] Adeeb A, Wisley D, Roberts S, Ellis A, Gates J, Skalet J, et al. Braking system, Espacenet (European Patent Office); 2016.
- [7] Obwieszczenie Marszałka Sejmu Rzeczypospolitej Polskiej z dnia 8 czerwca 2017 r. w sprawie ogłoszenia jednolitego tekstu ustawy – Prawo o ruchu drogowym, *Dz.U.* 2017 poz. 1260.
- [8] Obwieszczenie Ministra Infrastruktury i Budownictwa z dnia 27 października 2016 r. w sprawie ogłoszenia jednolitego tekstu rozporządzenia Ministra Infrastruktury w sprawie warunków technicznych pojazdów oraz zakresu ich niezbędnego wyposażenia, *Dziennik Ustaw* z dnia 29 grudnia 2016 r., poz. 2022, z późniejszymi zmianami.
- [9] Obwieszczenie Ministra Infrastruktury i Rozwoju z dnia 21 kwietnia 2015 r. w sprawie ogłoszenia jednolitego tekstu rozporządzenia Ministra Transportu, Budownictwa i Gospodarki Morskiej w sprawie zakresu i sposobu przeprowadzania badań technicznych pojazdów oraz wzorów dokumentów stosowanych przy tych badaniach, *Dziennik Ustaw* z dnia 10 czerwca 2015 r., poz. 776, z późniejszymi zmianami.
- [10] Czechowski K, Wilmowska-Pietruszyńska A. O potrzebie rehabilitacji kompleksowej. *Niepełnosprawność – zagadnienia, problemy, rozwiązania*, PFRON, nr II/2016(19); 2016.
- [11] Turbańska R, Woškowiak G. Kryteria zdrowotne w kwalifikacji osób kierujących pojazdami. *Hygeia Public Health*. 2016;51(91).
- [12] Ucińska M. Psychologia społeczna transportu, rozdział w: Odachowska E. (red.): *Badania kwestionariuszowe w psychologii transportu*, monografia, *Transport Samochodowy*; 2015.
- [13] Ucińska M, Odachowska E, Klamra M, Ściagała D. Wpływ zaburzeń psychomotorycznych na funkcjonowanie w ruchu drogowym, *Logistyka*, nr 3/2015; 2015.
- [14] Guzik-Makaruk M, Jurgielewicz-Delegacz E. Badania nad bezpieczeństwem osób z niepełnosprawnościami, w tym osób niewidomych i słabowidzących, uczestniczących w ruchu drogowym. *Niepełnosprawność – zagadnienia, problemy, rozwiązania*, PFRON, Nr II/2016(18); 2016.
- [15] Sybilski K, Małachowski J. Modelowanie sił mięśniowych i ich wpływ na zachowanie kierowcy niepełnosprawnego w trakcie zderzenia czołowego, materiały konferencyjne: XIII Konferencja Naukowa “Majówka Młodych Biomechaników im. prof. Dagmary Tejszerskiej”, *Ustroń*; 2016.
- [16] Ucińska M, Stasiak-Cieślak B. Wstępna analiza sytuacji kierowców z niepełnosprawnością w Polsce w kontekście bezpieczeństwa ruchu drogowego, *Transport Samochodowy*, nr 3-2015; 2015.
- [17] Ucińska M, Odachowska E, Klamra M, Ściagała D. Stopień niepełnosprawności a percepcja ruchu drogowego, *Logistyka*, nr 4/2015; 2015.
- [18] Szafranśka A, Sybilski K, Małachowski J. Koncepcja uchwytu na kierownicę dla osób niepełnosprawnych, *Logistyka*, nr 4/2015; 2015.
- [19] Stasiak-Cieślak B, Dziedziak P, Sowiński A, Jaroński W. Kontrola techniczna pojazdów z adaptacjami przeznaczonymi dla osób z niepełnosprawnościami. Pilotażowe badanie ankietowe wśród diagnostów stacji kontroli pojazdów, *Transport Samochodowy*, nr 3/2016; 2016.