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ASSESSMENT OF USABILITY OF DIGITAL SIDE MIRROR TECHNOLOGY CONCERNING PARKING SPEED AND ACCURACY

Jakub POVÝŠIL¹, Michal HRUŠKA^{*1}, Stanislav JELEN², Petr BENDA³, Anna Maria ZIFIA⁴,
Tomáš BENDA³, Nikita VOJTĚCHOVÁ⁵, Jiří BRADNA¹

¹Czech University of Life Sciences Prague, Faculty of Engineering, Department of Technological Equipment of Building, Prague, Czech Republic, kuba.povysil@gmail.com (J.P.), jabko@tf.czu.cz (M.H.), bradna@tf.czu.cz (J.B.)

²Czech University of Life Sciences Prague, Faculty of Engineering, Department of Machinery Utilization, Prague, Czech Republic, jelen@rektorat.czu.cz (S.J.)

³Czech University of Life Sciences Prague, Faculty of Economics and Management, Department of Information Technologies, Prague, Czech Republic, bendap@pef.czu.cz (P.B.), bendat@pef.czu.cz (T.B.)

⁴Tilburg University, Tilburg School of Social and Behavioral Sciences, Department of Cognitive Neuropsychology, The Netherlands, annazifia@gmail.com (A.M.Z.)

⁵Czech University of Life Sciences Prague, Faculty of Engineering, Department of Material Science and Manufacturing Technology, Prague, Czech Republic, xvojn002@studenti.czu.cz (N.V.)

*correspondence: jabko@tf.czu.cz

This paper focuses on the comparison of traditional and digital side mirrors in passenger cars during parallel and perpendicular parking maneuvers. The study was conducted on a closed testing ground, where data were collected through field measurements involving a relatively homogeneous group of drivers. The primary aim of the research was to evaluate how the use of digital mirrors affects parking speed and accuracy compared to traditional mirrors, and whether this new technology offers tangible benefits in terms of usability and safety. The key parameters, such as the time required to complete the parking maneuver and the accuracy of the vehicle's positioning within the parking space, were recorded during the measurements. The data obtained from this research were then subjected to Pearson's Chi-squared test to evaluate the drivers' dependence and comfort with the digital side mirror technology. The analysis of the collected data revealed statistically significant differences between the two types of mirrors, with results indicating lower accuracy and higher time consumption when parking with digital mirrors compared to traditional ones. Based on these findings, it can be concluded that digital side mirrors, although representing a modern technological advancement, may have limited practical usability in terms of safety and efficiency, particularly in maneuvers requiring a high degree of precision. Therefore, the study highlights the need for further research and optimisation of this technology to ensure it can be fully utilised in everyday driving, providing drivers with comparable or greater comfort and safety than traditional side mirrors.

Keywords: car; driver; assistance systems; angle of view; rear view; overtaking; parking

Since its inception, the automotive industry has seen major transformations in both exterior and interior aspects, including changes in appearance and the materials used in production. Power units have become more effective and reliable, cockpit design has become more sophisticated and thoughtful, and additional features have been built into the vehicles to make the driving process easier for drivers. In addition, highly durable materials are now used, which also helps to ensure driver safety at all times (Rizzoni et al., 2009; Taub et al., 2007). Until 2015, the cockpit of cars did not undergo any revolutionary changes as the priority was primarily vehicle operability and handling (Regan and Strayer, 2014). Intelligent Transport Systems (ITS) and Advanced Driver Assistance Systems (ADAS) use information and communication technologies in vehicles and transport infrastructure to improve safety, efficiency, comfort, and reliability. The set of ITS technologies implemented in cars is referred to as ADAS (Arena and Pau, 2019; Hilgers and Achenbach, 2021; Shaout et al., 2011). These ADAS are intended to provide additional assistance and support

the driver in their driving tasks and they are also used in trucks to ensure safety (Hilgers and Achenbach, 2021). In this paper, one such ADAS, particularly the Digital Side Mirror (DSM) technology will be used to evaluate the ease of parking maneuvers compared to conventional side mirrors.

The Digital Side Mirrors (DSM) technology is one of the new advanced driver assistance systems (ADAS) being researched as it is rapidly developing (Lu et al., 2005). The effectiveness of this new technology needs to be evaluated meticulously to ensure driver safety and increase the assistance provided to drivers. Common problems that arise without a driver-centered design approach include information overload, insufficient driver assistance, drivers' over-reliance on technology, negative behavioral adaptations to the technology, and overall misuse of the new technology (Large et al., 2016; Pampel et al., 2020; Regan and Strayer, 2014; Babu et al., 2022). The adoption of the new ADAS depends on various factors that have been investigated over the years. There are many methods used in evaluating the acceptance rate of the driver assistance

system and some of them are stated in the article in the late 90s' by Van Der Laan et al. (1997). It can be argued that the choice of a passenger car is also based on ADAS and its sub-systems that would give the driver a sense of additional safety (Brookhuis et al., 2001; Lu et al., 2005).

The DSM technology aims to enhance the vehicle's aerodynamics, fuel efficiency, and interior noise reduction (Chu et al., 2018). Today, the DSM technology is no longer only used in functional prototypes, but also in many mass-produced cars. As an example, the Lexus ES, introduced back in 2018, was the first mass-produced Japanese car to feature the DSM technology, with the DSM display positioned where the dashboard meets the A-pillar trim (Capparella, 2018). One of the key advantages of DSM displays is that they can be positioned virtually anywhere in the vehicle cab within the driver's field of view (Beck et al., 2017; Large et al., 2016; Murata and Kohno, 2018; Hruška et al., 2023).

The main objective of this research is to evaluate the speed and accuracy of the rear parallel and perpendicular parking maneuvers using a dynamic on-road testing methodology. This study not only investigates the comfort and ease of use of the technology under investigation but also systematically compares the differences in speed and accuracy of parking using conventional mirrors and the new digital side mirror technology. Driving performance is statistically analysed using various quantitative statistical models to understand the relationship between the measured parameters and the overall efficiency of the new DSM technology. This study hypothesises that using a DSM display improves driving efficiency compared to a conventional side mirror system. The research evaluates the applicability of the DSM technology, but in addition, it creates a basis for future research and development.

The following research questions and resulting hypotheses were established to achieve the above objectives. The first research question is whether drivers parked more accurately with electronic or conventional mirrors. The second research question is whether drivers parked faster with digital or conventional mirrors. Based on preliminary expert testing, the following hypotheses were derived from the research questions. The first hypothesis states that there will be a statistically significant difference between the accuracy of parking maneuvers when using conventional or digital rear-view mirrors and the digital technology will be significantly less applicable. The second hypothesis asserts that parking with a digital mirror took

statistically considerably longer for the average person than parking with a conventional mirror.

Material and Methods

Description of demographics

A relatively homogeneous group of 176 test drivers participated in the field research; however, for this particular study, data from only 91 participants were used. The reason for this narrowing of the sample was the need to use only completely valid and accurate data, which could not be collected from all participants due to the difficulty of testing. To facilitate further statistical analysis, data on the socio-demographic parameters such as age, gender, previous driving experience, etc. were collected from the participants. The age group of participants ranged from 21 to 54 years. All the test drivers who participated in this study had to be valid holders of a Group B licence (for driving a passenger vehicle), were required to have healthy eyesight with clear orientation ability, no other musculoskeletal limitations or other medical complications that could bias the overall results, especially concerning smooth vehicle control during any parking maneuver. Preliminary questioning ensured that none of the test drivers involved had previous personal experience with the DSM technology.

Description of location

For the purpose of field testing, a closed test polygon was chosen where non-homologated vehicles can be operated without any further restrictions. All tasks during which data were collected to verify the accuracy and safety of the parking maneuvers were conducted using real dummy vehicles, parked in precise positions (Fig. 1) that remained constant throughout the measurement period. The positions of the parked vehicles were chosen according to the standardised parking spaces as specified in the standard (ČSN 73 6056, 2011) (Fig. 5 and 6).

Description of equipment

Two completely identical Škoda Superb III test vehicles were used for testing purposes. One vehicle was left unchanged with conventional rear-view mirrors (marked as vehicle B). The second car was modified by removing the two conventional side mirrors and replacing them with a system



Fig. 1 Real vehicle dummies were used to demarcate parking spaces

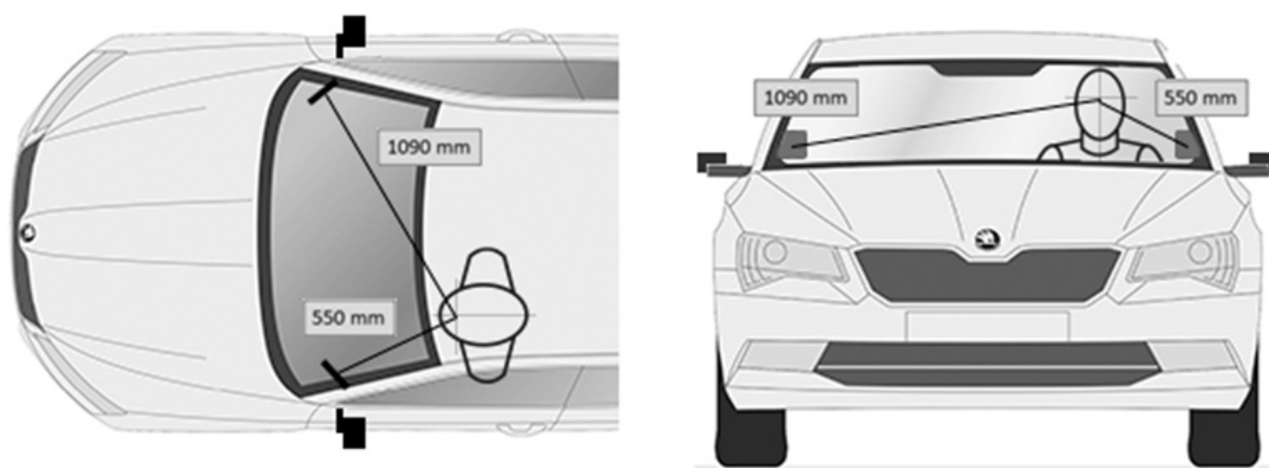


Fig. 2 Dimension to the side mirrors from the centre of the head of 50 percentile human head

of digital side mirrors on both sides of the vehicle (marked as vehicle A). The image was captured using the "Sony CyberShot Camera DSC-RX0 Mark II" (Sony, 2019), and displayed on the "FeelWorld monitor FW570" (FEELWORLD, 2017). Detailed parameters of both devices are listed in Table 1. This specific camera was chosen for the experimental setup because its focal length is similar to that of the human eye (Wang et al., 2022). The professional monitor "FeelWorld monitor FW570" was chosen as the optimal one for displaying the image provided by this particular camera model because it has a high resolution, which reduces the pixelation of the displayed image. The connection between the sensing and display elements was provided by a special interconnecting cable. The positioning of the display was chosen to match the angular positioning of conventional rear-view mirrors in the driver's field of vision. The Hip-Point (H-point) or Seating Reference Point (SgRP or R-Point) position was utilised to ensure the accurate placement of conventional side mirrors, adhering to the standards outlined in the Federal Motor Vehicle Safety

Standard (FMVSS) 111 (NHTSA, 2013) and the United Nations and Economic Commission of Europe (UNECE) regulation R46 and regulation R324 revision 4 also mentioned as ISO 16505 (ISO 16505, 2019). Based on this, normalised driver position in the vehicle, the distance to the right DSM display was defined as 1090 mm and the distance to the left DSM display as 550 mm, measured from the center of the head at the 50th percentile position of the adult, European male dummy (Fig. 2), which is referred to as the optimum driving position in the vehicle according to the SAE J826 standard (SAE J826, 2021). The positions and angles of the two DSM displays in the vehicle were locked and could not be modified by any of the drivers. The DSM displays were positioned at an angle that provided the same image as corresponded to the driver's line of vision. The entire setup simulating the commercial DSM used in the research had an image delay of approximately 0.3 seconds, which is quite competitive to the technologies used in mass-produced vehicles.

Table 1 Equipment description and specifications

Equipment	Description	Specification
Display	screen size	5.7"/14.5 cm
	resolution	1920 × 1080 p (16 : 9)
	brightness	460 cd·m ⁻² (LED)
	dimension	(5.8 × 3.2 × 0.7)"/(14.8 × 8.2 × 1.9) cm
Camera	resolution	4800 × 3200 p (3 : 2)
	sensor type	BSI – CMOS
	processor	BIONZ X
	focal length (equiv.)	24 mm
Sony DSC-RX0 II	max. aperture	F4
	normal focus range	7.87"/20 cm
	resolution	1920 × 1080 at 25 fps
	accuracy	0.04 s
Tobii glasses 2		



Fig. 3 Škoda Superb III modified to use DSM digital rear-view mirrors

Description of tasks and data collection

The tests described in this paper were one part of a large study in which participants performed dynamic tests simulating overtaking in addition to parking tasks. The parking tasks were always performed second, so all respondents had a comparable starting position regarding experience with the technology under study. The parking test was divided into two basic categories according to the types of parking that occur most frequently in practice – the back parallel parking maneuver and the back perpendicular parking maneuver.

Figure 3 shows a digital camera placed outside the car and a display used to show the image captured by the camera placed inside the door. This system replaces conventional side mirrors. The location of the camera and display is very similar to the location of the classic mirror on a conventional car. The test vehicle was equipped with a camera and a display on both.

Participants performed the parking tasks sequentially in both test cars, equipped with the conventional side mirrors and DSM technology, in order to compare results and data for statistical analysis. Participants started the test alternately in one or the other vehicle to avoid biasing the data obtained from previous experience in favour of one of the tested technologies. All tests were conducted

outdoors, during the month of September, and in weather conditions that maintained good lighting conditions for all participants.

The view of the driver in the vehicle cabin is shown in Fig. 4. The participants of the study used tracking Tobii glasses 2 (Tobii AB, 2017) with the camera during the performance of the test tasks. The essential data from these glasses were obtained.

At the start of the task (Fig. 5), the test vehicle was at the starting point. The participant then waited for instructions from the research assistant. After receiving instructions from the research assistant, the participant performed a reverse parallel parking maneuver starting from the starting location. Once satisfied with the performance, the participant signalled the research assistant to complete the task by lifting both hands above the steering wheel.

The entire performance was recorded on onboard cameras and tracking glasses to accurately measure task time and further statistical analysis. The research assistant then measured the distance between the test car and other parked cars and the distance from the test car to the pavement for statistical analysis using a tape measure with a measurement accuracy of ± 0.5 cm (Fig. 7 and 8). This methodology was also used for the perpendicular rear-parking maneuver (Fig. 6).



Fig. 4 View from drivers' point of view from one of the parking tasks on the DSM display

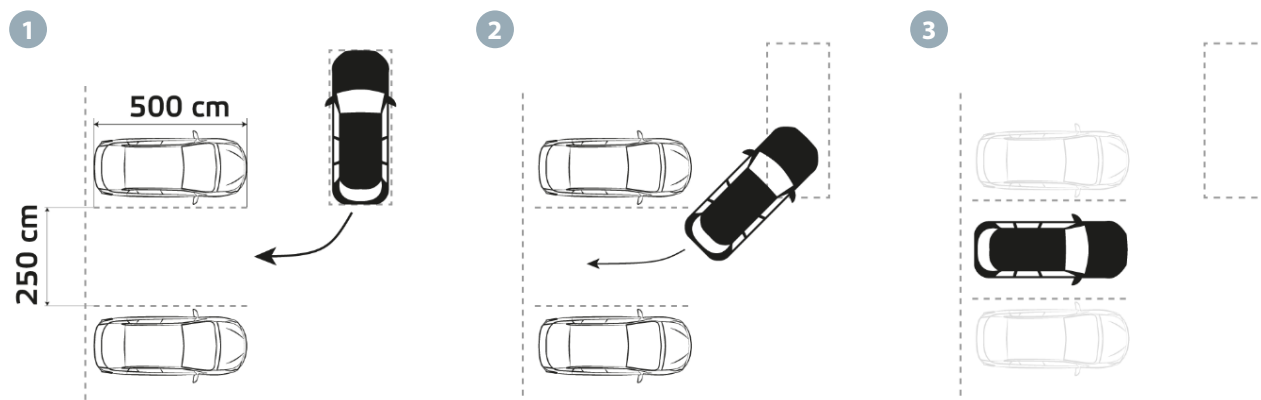


Fig. 5 Schematic representation of the individual steps of the perpendicular rear-parking maneuver task

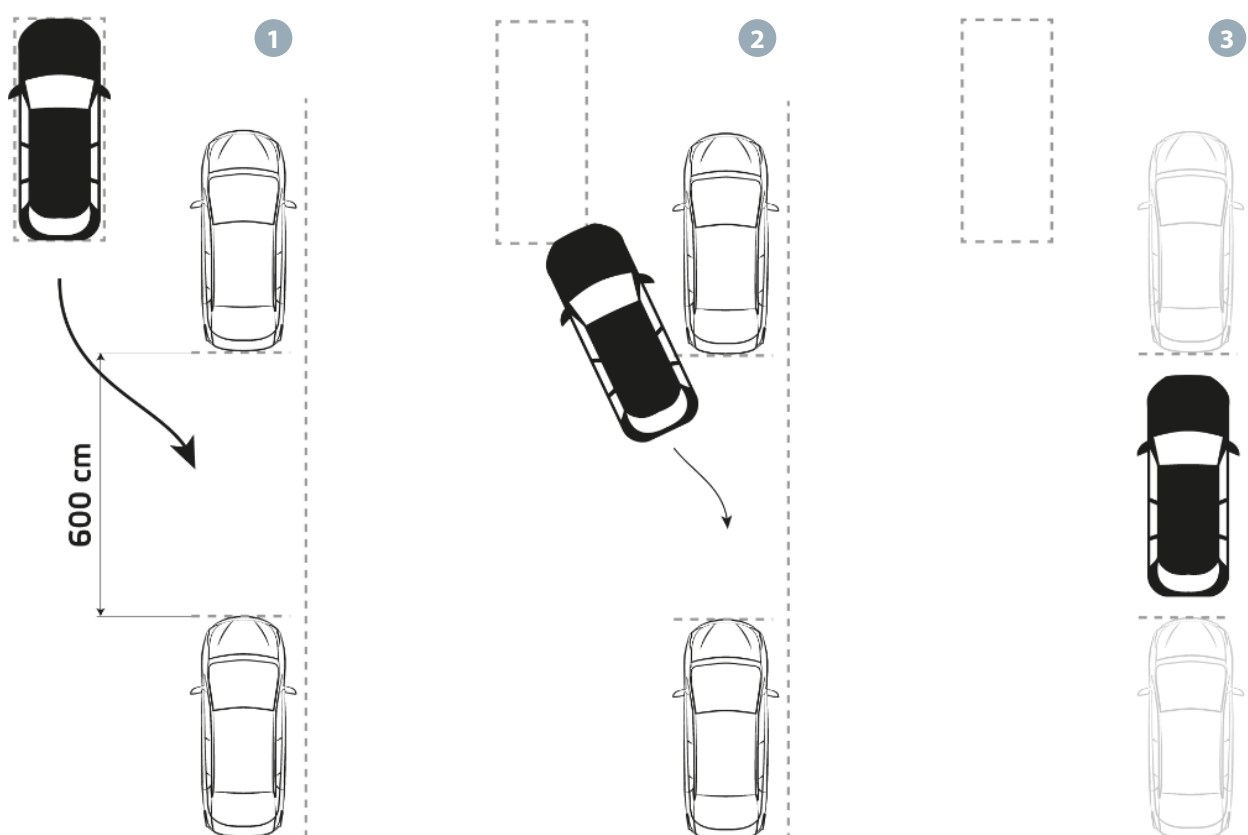


Fig 6 Schematic representation of the individual steps of the parallel parking maneuver test task

Result and Discussion

The parameters of the speed and accuracy of parking maneuvers were chosen to assess both technologies. While the speed of maneuver execution can be clearly defined and measured as the time between the start and the end of the maneuver, evaluating the accuracy of the maneuvers is considerably more complex. The optimal positions of the parked vehicles, which served as benchmarks for evaluating each task, were determined based on these postulates.

1. In the case of Back Parallel Parking, the most accurate condition is if C is equal to F and, at the same time, D is equal to E (Fig. 7).
2. The optimal distance (Y) from the "sidewalk", i.e. the values of D and E, is 35 cm for Back Parallel Parking (Fig. 6).
3. In the case of transverse parking, the most accurate condition is if G equals H and, at the same time, I equals J (Fig. 8).
4. The optimal distance from the "sidewalk" for Perpendicular Parking (K) is 30 cm (Fig. 8).

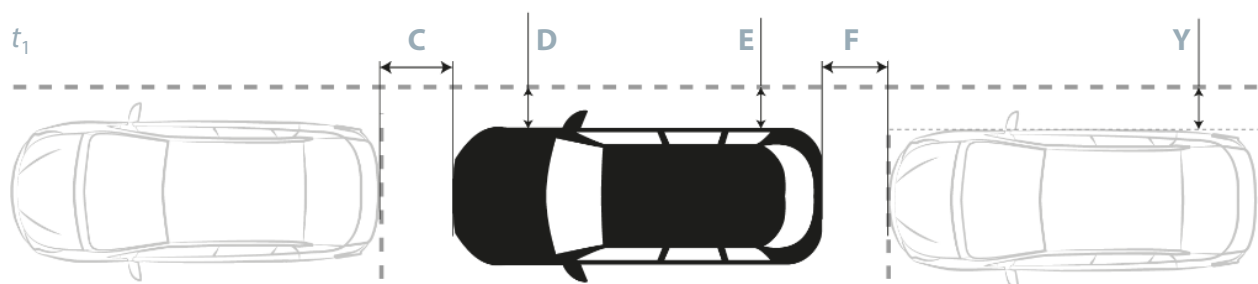


Fig. 7 Determination of parameters for the evaluation of the parallel parking test maneuver

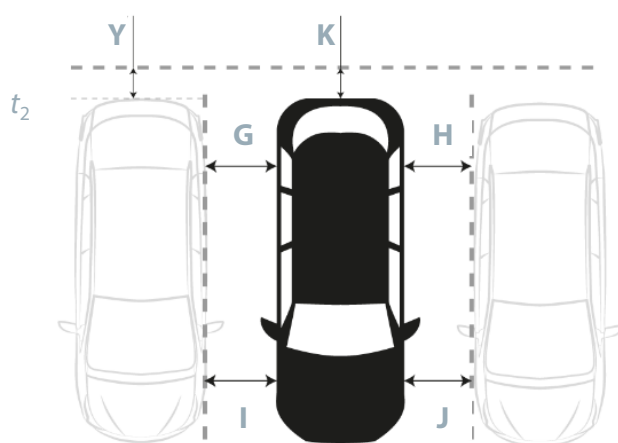


Fig. 8 Determination of parameters for the evaluation of the perpendicular rear-parking maneuver task

In Fig. 6, t_1 represents the time taken by the participant to complete the entire task of parallel parking; C and F represent the distance between the test car from the other parked vehicles when the parking maneuver is completed; and D and E represent the distance between the parked test car and the pavement.

In Fig. 7, t_2 represents the time taken by the participant to complete the entire task of perpendicular parking in the final described position; G and H represent the distance between the test car from the other parked vehicles in the axis of the rear wheels, I and J represent the distance between the car from the other vehicles in the axis of the front wheels when the parking maneuver is completed; and K represents the distance between the parked test car and the pavement.

Statistically significant dependencies were identified using contingency tables and the method of adjusted residuals. Measurement results were statistically analysed and evaluated using Pivot tables and Pearson's chi-squared test at a significance level of 0.05 as explained by McHugh (2013) and Wasserstein and Lazar (2016). Furthermore, the adjusted residuals method was used to refine and better interpret the found dependencies further.

Speed of parking

Based on the data presented in Table 2, it can be concluded that the difference in parking speed for both rear-view mirror technologies and both parking methods used is statistically significant. Drivers using digital rear-view mirrors parked on average 6.9 seconds slower in the Back Parallel Parking case and 4.3 seconds slower in the Back Perpendicular Parking case.

This time difference to the detriment of the digital mirror technology may seem insignificant, but there is no denying that it can act as a significant stressor for some drivers. The explanation for the worse performance of drivers with digital rear-view mirrors can be found in their ability to perceive the digitally mediated image correctly and a certain level of distrust in the reality of the mediated image. This was confirmed by a previously published study that asked the same group of respondents about their feelings when using the digital mirror technology. Only 55 percent of respondents said they trusted the digital image when driving (Babu et al., 2022).

Parking accuracy

Based on the results presented in Table 3, it can be concluded that the accuracy in parallel parking shows statistically significant differences; however, this difference

Table 2 Evaluation of the differences between conventional and digital rear-view mirrors for both parking modes depending on the time of parking operation

	Parallel parking	Perpendicular parking
Average time for digital mirrors (A)	53.1 s	42.8 s
Average time for conventional mirrors (B)	46.1 s	38.5 s
Difference in times (A–B)	6.9 s	4.3 s
Standard deviation (A–B)	22.7 s	11.3 s
p-value	0.02	0.01
Statistical dependence	confirmed	confirmed

A – car with digital technology, B – car with conventional technology

Table 3 Evaluation of the differences between conventional and digital rear-view mirrors for parallel parking maneuver depending on parking accuracy

	Front and rear gap C–F	Vehicle rotation D–E	Distance from pavement abs (Y–D) + abs (Y–E)
Difference of mean deviations abs (A)–abs(B)	22.3 cm	0.1 cm	1.7 cm
Standard deviation	44.1 cm	9.4 cm	20.0 cm
p-value	>0.01	0.48	0.29
Statistical dependence	confirmed	not confirmed	not confirmed

A – car with digital technology, B – car with conventional technology

Table 4 Evaluation of the differences between conventional and digital rear-view mirrors for perpendicular rear-parking maneuvers depending on parking accuracy

	Front gaps C–F	Rear gaps G–H	Distance from pavement abs (Y–K)
Difference of mean deviations abs (A)–abs (B)	22.5 cm	23.9 cm	-2.7 cm
Standard deviation	22.2 cm	26.2 cm	13.2 cm
p-value	>0.01	>0.01	0.91
Statistical dependence	confirmed	confirmed	not confirmed

A – car with digital technology, B – car with conventional technology

is only in terms of the gap in front and behind the vehicle. Drivers using the digital mirrors achieved an average error of 22.3 cm higher than for the conventional mirrors. On the other hand, regarding vehicle rotation and distance from the sidewalk, there was no statistically significant difference in parking accuracy when using either rear-view mirror technology.

This relative discrepancy can be easily explained based on the driver's realistic approach to using rear-view mirrors during a parking maneuver. When reversing into a parking space, the driver is entirely dependent on the image provided by the rear-view mirrors. Thus, his estimation of the distance to the vehicle behind him is also affected. However, the driver also uses other visual information, such as the position of the parked vehicles in front of him, to judge the rotation of the vehicle relative to the line of parked vehicles. The same is true for the distance from the pavement, where the driver is not so much trying to determine the optimal distance but rather trying to get his vehicles to overlap precisely with the other vehicles parked in the row. The use of rear-view mirrors for this maneuver is then minimal.

The difference in front and rear gap accuracy, which came out clearly against digital rear-view mirrors, can again be explained based on previous studies where respondents cited the inability to correctly estimate distances to vehicles displayed in digital rear-view mirrors as one of the most severe problems (Babu et al., 2022).

Based on the results presented in Table 4, it can be concluded that the perpendicular rear-parking accuracy shows statistically significant differences in both main values for both front and rear vehicle spacing relative to other parked vehicles. Drivers using digital mirrors achieved an average error of 22.5 cm and 23.9 cm higher for front and rear spacing than conventional mirrors. In terms of distance from the sidewalk, again, there was no statistically significant difference in parking accuracy when using either rear-view mirror technology.

Again, it is evident that in cases where the driver is forced to orient himself directly based on the information provided by the image, this relative difference can be easily explained by the driver's realistic approach to using rear-view mirrors in the parking maneuver. When reversing into a parking space, the driver is entirely dependent on the image provided by the rear-view mirrors. Thus, his estimation of the distance to the vehicle behind him is affected. However, the driver also uses other visual information, such as the position of parked vehicles in front of him, to judge the vehicle rotation relative to the line of parked vehicles. The same applies to the distance to the pavement, where the driver does not so much try to determine the optimum distance but instead tries to ensure that his vehicles overlap exactly with the other vehicles parked in the row. The use of rear-view mirrors for this maneuver is then minimal.

Also in this case, the rotation of a parked vehicle, the differences between digital and conventional rear-view mirrors can be explained based on previous published studies (Babu et al., 2022; Hruška et al., 2023), where a significant group of respondents pointed out the problematic distance perception and general image realism of digital rear-view mirrors, which subsequently leads to these unsatisfactory results.

Statistical dependencies on socio-demographic data

The measured data were further tested for possible dependencies on the input socio-demographic data. The gender and age of the respondents were selected. It should be noted that in neither case was any statistically significant dependence found.

Based on the above data, there are significant differences between digital and conventional digital mirrors when used in parking maneuvers. These differences are both in the time required to perform the maneuver and in its accuracy. It should be noted that, overall, drivers performed statistically

significantly worse when using digital mirrors than when using conventional mirrors. These results are somewhat at odds with similar research presented in 2018 (Murata and Kohno, 2018). However, these differences in the assessment of the effectiveness of DSM may be due to the difference in methodology, with participants in previous tests completing the tasks only on a simulator, thus missing a completely immediate, in-person assessment of the difference between DSM and conventional rear-view mirrors. From this perspective, it can be argued that evaluating the technology under real conditions offers more relevant results than those found only under simulator conditions.

For organisational reasons, the above-presented study used only respondents whose visual status was impeccable. However, it must be stated that this does not correspond to the real situation where drivers with various visual impairments, which are not always fully compensated for, are on the road. However, the authors of some previously published papers have concluded that even drivers with compensated eye defects have slightly lower confidence in the image provided by digital mirrors than healthy participants. This may be due to the problematic process of eye accommodation when re-focusing from distance to near, especially if the eye impairment is compensated by the use of dioptric glasses (Hruška et al., 2023), which may cause some discomfort for drivers with compensated eye impairments (Benjamin, 2006; Glasser and Campbell, 1999). Reducing image latency and improving the overall technological parameters of the camera and display could significantly improve the driver's confidence in these technologies and thus overall safety in these cases.

Conclusion

The aim of the research was to investigate and assess the applicability of digital side mirror technology in terms of parking speed and accuracy. Based on the data and conclusions presented above, it can be concluded that there are significant differences between conventional and digital mirrors in passenger cars when used for parking manoeuvres. It can also be concluded that conventional mirrors are safer and have a higher level of usability than digital mirrors in this aspect.

Although the responses observed were related to testing in passenger cars, the technology can also be applied to agricultural or construction machinery or trucks. Although the DSM technology is already in production use, not many similar studies have yet been conducted to collect accurate data during traffic situations when drivers are using this technology during parking maneuvers. However, studies on the use of camera systems as rear-view mirrors have been published, reporting on the benefits on the road and drivers' practical experience with this technology (Ayoub et al., 2021; Beck et al., 2017; Murata and Kohno, 2018; Pampel et al., 2020; Wittmann et al., 2006). The authors of these studies more or less agree that the applicability of this technology and its impact on road safety is questionable, to say the least.

Last but not least, the results presented in this study could serve as a data and knowledge base for further research to help refine the above findings or otherwise serve to further research addressing the issue of the DSM

technology. Further, the results of this research can be applied to the design process of DSM systems, particularly with respect to the placement of displays in the vehicle cabin, with a focus on ergonomics and overall functionality of the technology with the goal of enhancing driver performance.

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